PROBLEMS OF SCALE:

AN O.R. / SYSTEMS APPROACH

(1 volume)

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Submitted for the degree of PhD

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May 1990

C O N T E N T S

LIST OF TABLES

LIST OF FIGURES

A C K N O W L E D G E M E N T S

My thanks are due to a number of people who read parts of the material of this thesis and made many useful comments. In particular I would like to thank Brian Arthur, Peter Beck, John Buzacott, Graham Douglas, Gerard Fairtlough, Ian Mitroff, Salamah Pope, Maurice Shutler, John Stringer and Aaron Wildavsky.

Many people were interviewed in the course of the research. Some are acknowledged directly (Chapter 6); my thanks are due to anonymous others who have indirectly contributed by increasing my understanding of the problems of scale by giving of their time and experience.

A particular debt is owed to colleagues on the Aston-Warwick Scale Project: David Collingridge, Peter James and Michael Thompson. I learnt much from them, and benefitted considerably from their advice, encouragement and criticism in differing measures. Mike especially showed me new ways of looking at the world. The work of this project was financially supported by the Leverhulme Trust.

I gratefully acknowledge the financial support of the SERC for one year of full-time study. The University of Warwick waived my fees as a part-time student whilst I was a member of the University staff.

Above all I owe thanks to my supervisor, Rolfe Tomlinson, who first interested me in this area. In particular Rolfe has supported me with gentle supervision, amazing tolerance of deviations into unusual fields, and excellent editorial advice.

Finally, my thanks to my friends and relations for putting up with me during the sometimes apparently endless months and years of getting all of this down on paper.

D E C L A R A T I O N

Some parts of the material included herein have been used in other places:

Chapter 2 has appeared as "The Development of the Theory of Economies of Scale", Warwick Papers in Management No.2 (1986).

The model described in Chapter 3 is an improved version of a simulation developed as part of my dissertation for the degree of MSc in Management Science and Operational Research, School of industrial and Business Studies, University of Warwick (1983), entitled "A Critical Examination of Economies of Scale in Production Systems". The original work was described in "Determining Appropriate Scale for Production Plants" by R C Tomlinson and P J Tayler, invited paper to CHEMRAWN-III conference (1983).

The material outlined in Chapter 6 is not all my own original work, but arose from joint work on the Aston-Warwick Scale Project. Part of this Chapter was presented by me under the title "A New Approach to Problems of Scale" at EURO-VIII (conference of the European Operational Research Societies) in Lisbon (September 1986). The general discussion has been presented in "The Surprise Game: An Exploration of Constrained Relativism" (by) M Thompson and P Tayler, Warwick Papers in Management No. 1 (October 1986), in "Environmental Rationalities" P James, P Tayler and M Thompson, UK Centre of Economic and Environmental Development Discussion Paper No. 6 (January 1987), and in "Plural Rationalities" P James, P Tayler and M Thompson, originally presented to conference on 'Analysisng the Inchoate: Inter-relationships in Complex Systems', Cornell University (April 1987).

SUMMARY

The history of analyses of scale and the conventional reductionist methodology are briefly recounted in the first chapter of the thesis. A detailed examination is then made of the theory of economies of scale and its development since the days of Adam Smith. A comprehensive survey shows that the description provided by conventional economic theory is quite unrealistic, and has been dictated by the demands of Neoclassical ideas of equilibrium. It is shown that the available empirical evidence does not easily allow conclusions to be drawn about the optimal scale of plants or enterprises.

A simple simulation model then demonstrates that static economies of scale alone are insufficient to determine "optimal" scale - dynamic diseconomies depend upon environmental context and uncertainties of forecasting future demand.

The question of technological change is closely bound up with issues of scale. The principle of bounded rationality is applied to deduce some conditions about the nature of technical change using Heiner's "Reliability Condition". The existence of "technological heuristics" (such as a bias in favour of scale-augmenting innovations) is predicted. The argument is illustrated with the use of a computer simulation of successive process innovations in a stylised chenical plant.

Conflicting ideas about "optimal" scale in electricity generation, papermaking, brewing and cement manufacture are examined. These views are found to be explicable by borrowing the theory of fourfold cultural bias from the field of social anthropolgy.

An Evolutionary Model of Increasing Returns (EMIR) is developed as a computer simulation. This model demonstrates that the restrictions imposed by conventional economic theory can be overcome in a dynamic economic model; economies of scale and technical change are married with plural rationalities to provide a range of findings on industry structure. Market share is found to be a more important determinant of industrial success than economies of scale.

EMIR is used to demonstrate the phenomenon of technological "Lock-In"; important policy choices may be determined by small random events as critical points. Market selection mechanisms cannot be relied upon to optimise, whether in scale decisions or other important policy choices.

The thesis concludes with a discussion of the use of plural models to go with plural rationalities in the analysis of policy issues.

Chapter 1: Single Vision or Multiple Perspectives? A Systems Approach to Problems of Scale

1. INTRODUCTION

The original purpose of this research was to provide assistance to decision-makers faced with "Problems of Scale". That is, it was initially conceived in terms of developing and improving specific analytical techniques to help decide how large new elements of productive capacity should be. This might have been built upon the textbook "U-shaped" scale-cost curve, possibly identifying the circumstances under which it would be applicable, and the additional factors which should be considered in employing it.

However, examination of the theoretical basis of this potential tool for the decision-maker revealed serious problems. The assumptions underpinning this approach were found to be wholly inadequate. The concept of the "optimum" scale of operations was not useful in the face of considerable technological, economic and perceptual uncertainties. It has become clear that questions of technical change, of the beliefs or "culture" of the organisation concerned, and of the sheer unpredictability of the environment are all significant.

The research has therefore developed away from the original focus on the immediate problems of the decision maker, to try to develop a new understanding of the scale problem. The insights gained have been combined to produce an evolutionary model of the processes involved. This new simulation model shows that theory need not be hide-bound by the restrictive assumptions employed in the past. It provides a tool for analysing industry development which has enabled some important conclusions to be drawn, both for the policy analyst and for the individual industrial decision maker.

The thesis also considers, in the final chapter, the methodology used for studying scale problems, and some general lessons which can be drawn for other major problems of industrial and social choice.

2. HISTORY

The problem of determining the appropriate scale of a new production plant has always been with us, but it has reached an increased degree of prominence and controversy in recent years. This is partly because the inbuilt belief of many planners and designers that increased size is necessary for economy and market dominance has received a number of recent shocks, and partly because of the reaction against giantism summarised by Schumacher's famous phrase "Small is Beautiful".

The Venice arsenal of the fourteenth century is sometimes cited as an example of an early factory, although in fact it was simply a collection of craftsmen and artisans working independently under the same roof. The factory system evolved through the Industrial Revolution as a means of concentrating workers and specialised machinery for the purposes of co-operatively carrying out complicated, multi-stage manufacturing processes. Perhaps the archetypal factory form was reached with the giant Ford car plant which in the early 1920's employed over 60,000 people and eventually produced millions of vehicles.

The vertically-integrated Ford works required enormous quantities of raw materials; it could only come into being in the age of mass communications- railways for transport of inputs and outputs, and the telephone for the management of geographically separated but interdependent functions. The giant "manufactory" had the effect of concentrating the population and was a force for rapid urbanisation throughout the nineteenth and early twentieth centuries, posing new social problems. De-skilled production line workforces had to be organised in large numbers, and Fordism created the conditions for the creation of mass trades union movements. The management of the new industrial armies posed novel problems, as did the need to be responsive to changes in the huge new national and international markets which products such as the model-T Ford had themselves created. Bureaucracy, as old as the Pharaohs, found its apotheosis in the great Soviet GOSPLAN industrial blueprints. Thus a whole range of new and complex, interlocking and connected problems are raised by the great increases in scale which have surged through the last two centuries.

The reasons for the increasing resistance to the idea that "big is better" during the last two decades are similarly complex. In part, the rapid expansion in demand in many areas of the economy during the late 1950s and 60s allowed scale mistakes to be swept under the carpet; plants too large for the market this year would be fully-utilised next, so why worry. The worldwide economic contractions beginning in the mid-70s, exacerbated by rising commodity prices and by the oil price shock of 1974 in particular changed that situation drastically, making planning errors much more visible- and more expensive. General increases in the post-war standard of living in the industrialised countries initially fuelled demand for mass-produced goods, but saturation stimulated desires for more differentiated products produced at smaller scale in different ways.

Faith in "Big Science" has been weakened: for example, the optimism of the early '50s which speculated that nuclear-generated electricity would be so cheap that it wouldn't be worth metering it, has dwindled to the point that, in the USA at least, nuclear energy was being seen as uneconomic in competition with conventional sources even before the near-disaster of Three Mile Island. In Britain new super-ministries such as the Department of the Environment matched the monolithic nationalised industries, and all were labelled "bureaucratic", "out of touch" and "inefficient" in the popular mind by 1980. In the late 1980s the political agenda of Right and Left talks about reducing the power of the State, decentralisation, and privatisation. In the Communist world the reaction against centralised planning, unaccountable bureaucracy and inefficiency has been even stronger. Finally, the public image of the giant multinational corporations has not been improved by publicity surrounding operations in some Third World countries.

The problems of scale are many and complex. Firstly economic efficiency- is it true that bigger plants are always cheaper to build and run? Even if they can be built at a lower cost per unit of output, many managers attest to the reality of the problems mentioned above- problems of retaining effective control over the giant factories, and of being able to effect real strategic change in large international organisations. Secondly there are technical problems in always seeking to build the biggest plant; technology can be pushed to the limit, or even beyond; reliability and underperformance have been found to be problems for some new giant installations.

Thirdly, there are difficulties associated with building production units which account for a large proportion of their relevant market. Risks are greater than when a number of smaller plants are operated because of the "all your eggs in one basket" syndrome, and flexibility is reduced. Forecasting becomes much more important, particularly when larger units tend to have longer planning and construction lead times.

Finally, a quantum leap in size often brings into play qualitatively new factors which were not a problem at the previous scale of production. Setting up a small workshop to build automobiles is one thing; planning a Detroit factory is quite another, involving problems of securing raw materials, arranging dedicated transport facilities, massive recruitment, buying hundreds of acres of suitable land and and raising immense amounts of capital. These are qualitatively different from finding a small site, arranging a loan with the bank and placing an advertisement in the local paper. Complexity is often bound up with scale, and neither are respecters of disciplinary boundaries.

3. PREVIOUS APPROACHES

There is little in the literature to help the planner decide on appropriate scale in circumstances where there is rapid technological change and a turbulent economic environment. Part of the difficulty lies in the fact that most of the research undertaken has been strictly disciplinary in nature, whereas in reality a broadly inter-disciplinary approach is needed.

Three main disciplinary approaches have been explored in the past. Firstly there has been much discussion of "economies of scale" in the economics and business studies disciplines. (See Gold (1981), and the next chapter.) Secondly, sociologists and organisational behaviourists have been engaged in a rather different study of the relationship between the size and the structure of organisations (Dewar and Hage (1978), Dale (1982)). Managers have faced a trend towards giantism in their organisations, both state-owned and private. Thirdly, engineers have long been involved with the practical problems arising from the ever-increasing sizes of buildings, bridges, machinery, vehicles, factories and other production units. Indeed it seems that the scale of almost every area of human activity has been growing since history began. However, the perception that all these specialist areas confronting the difficulties arising from "scaleup" problems might have some common elements which would repay study in their own right has only come about very recently.

The first serious interdisciplinary approach to the subject was in a research project at the International Institute of Applied Systems Analysis, initiated by Rolfe Tomlinson in 1978. A paper under the title "Determining Appropriate Scale for Production Plants" was prepared by Cantley and Glagolev (1978) in the same year, in which they reviewed the current state of knowledge and made an initial attempt at structuring the field. This paper was used to help in planning an international conference held in 1979, which was the first time that representatives of the different disciplines involved (from many countries) got together to discuss the issues involved. The proceedings of that meeting were subsequently published (Buzacott, Cantley, Glagolev and Tomlinson 1981).

Subsequently a multidisciplinary research effort was initiated in IMRAD at the University of Warwick with the aid of a grant from the Leverhulme Trust under Rolfe Tomlinson and David Collingridge of the University of Aston. This thesis is largely a result of work carried out on that project.

4. METHODOLOGY

Approaching such a complex research area as Problems of Scale demands an appreciation of the past attempts to understand scale, and of the reasons why they have been at best only partially successful. This in turn requires that we look at the methods which have been used to tackle these questions. Some features of the philosophy underlying past methodology will be discussed in this section, and counterposed with the emerging "Systems" model of the world. Many themes identified in this section will return in later chapters.

It seems to me that the essential thing past approaches to the scale problem have in common is that they are essentially <u>reductionist</u>. This element will be examined first.

The method of reductionism was first articulated in Western thought by the French philosopher and mathematician Renee Descartes. The reductionist approach to a complex problem is to divide it up, or reduce it, into a set of constituent elements. These simpler elements may be much easier to understand and analyse, and their behaviour as separate units is likely to be far more comprehensible than that of the original whole. If not, then the division into smaller and simpler parts must be continued further until this is possible.

The Age of the Enlightenment made powerful use of this means of understanding the world, and the reductionist scientific method has ultimately proved to be one of the most successful cultural innovations in human history. Perhaps its most impressive achievements were made in combination with another profound discovery- that mathematics could be employed to describe and explain events in the natural world. Newton's invention of the calculus led to a brilliantly simple and elegant model of the motion of the bodies of the Solar System.

This model can be taken as a symbol of the triumph of the Enlightenment. The movements of Sun, Moon and planets, sometimes seen in the past as capricious and signifying the wanton and uncontrollable character of Nature and God, could now be predicted from a few simple laws from which there were no deviations. The natural world was like a piece of clockwork machinery. The stars traced out their orbits against a single set of coordinates set down by God (and parametrised by Newton). The former sat, omniscient, needing only rare interventions to ensure the perfect running of the Universe, whilst the latter could predict the future with mechanical confidence. (Laplace later asserted, under pressure from Napoleon, that God was not really necessary- the model was so complete that no intervention was required.) The Harmony of the Spheres gave way to a perfect equilibrium system in which history was redundant- all that was needed was the position and velocities of the bodies to determine their futures.

The world, then, could be interrogated by the reductionist approach, described by mathematical and deterministic laws, and could be predicted, at least in principle. The way was clear for the development of a vast body of physical science which stood intact at least until the beginning of this century.

This was not to everyone's liking, we may observe in passing; a few cranky mystics and madmen have always railed against progress in every age:

> "May God us keep
> From Single vision and Newton's sleep!"

exclaimed William Blake. To Blake the sterile operation of Reason alone was insufficient for comprehending the world, and the reductionists and mathematicians were aspects of Urizen ("your Reason"), a kind of Devil-figure.

The successes of reductionism, and of rationalist scientific thought generally, have led to the application in the social sciences of the same kinds of methods which have succeeded for so long in the physical sciences. Complex problems in the human world could, it seemed, be tamed by the grand alliance of reductionism and mathematics. The behaviour of the economic and social universes could be mapped and measured, and their futures predicted and optimised by Newton's descendants. The social sciences enthusiastically embraced the language, philosophy and methodology of physics.

Here, however, serious problems have arisen, and they apply to Problems of Scale as much as to anything else in the human "sciences" area. One difficulty arises from the subject matter. The social sciences deal very much with people's perceptions and values- in other words, with things which cannot be directly observed. Indeed, are these "things" in the usual sense at all? The reductionist approach has been tremendously successful, but yet it carries within it the seeds of its own destruction. Reducing a problem to its constituent parts is all very well, but what happens when the really interesting thing is the relationship between the constituents rather than their individual properties?

For example, it is quite possible to reduce a motor car to its components and give a description of it in those terms. But that does not tell us the really important things about the car- for example, what it was for. Describing a carburettor, a spark plug, a piston, and a fan, will only take us so far if we are not told that they join up in a particular way to make a motor. In turn, descriptions of motor, chassis, transmission, steering and tyres are incomplete unless it is known that they can be joined to form part of a transportation system (which includes roads, facilities for fuelling, and so on). Reductionism is excellent for analysis but it is not terribly good at assisting <u>understanding</u> by itself. Furthermore, the scientific foundations which seemed to justify the approach are no longer as secure as they once seemed.

Just at the moment that social science took on the mindset of Classical physics, physics itself started to undergo catastrophic change, with results which are still not very widely understood. Newton's single frame of reference had to be abandoned for Einstein's multiplicity of relative frames. Determinism, even in principle, has been subverted by quantum mechanics. The detached observer sitting outside the world-machine has gone, and consciousness itself, according to some accounts, has become an operator in wave mechanics. Indeed, some of the most brilliant physicists now sound more like the mystics and cranks of the Enlightenment. (See for example Bohm (1980) and Capra (1975).)

The result is crisis for the philosophies which justify many of the ways in which we go about seeking knowledge and the ways in which we use that knowledge. It is a crisis in the Kuhnian sense also- the old paradigm is under threat, and the new has not clearly established itself. There are some pointers to the way that things may go, although in some ways it is easier at the moment to describe the "New Paradigm" in terms of what it is not rather than what it is. In what follows I shall try to identify what seem to be the most interesting and important themes, particularly with regard to an Applied Systems approach to Problems of Scale. Jantsch, Prigogine and Allen have been among the most significant thinkers here, though it is crucial that no single one has a monopoly or a clear pre-eminence in the "invisible college" of the New Paradigm. (See: Jantsch (1980), Jantsch and Waddington (1976), Prigogine and Stengers (1984), and Allen et al (1985).)

The first and most important element of the new approach is that it is <u>anti-reductionist</u>. It concerns itself with the <u>emergent</u> properties of a system; that is, with precisely those effects which are caused by the operation of the whole, and which deal with the relationships between the parts, missed by the reductionist approach. Emergent properties are phenomena of the whole which are qualitatively different from the behaviour of the parts and could not be predicted by considering the behaviour of the parts alone. An example would be a very simple single-cell organism. This can be described in terms of its constituent organic molecules, but the important things about it- its limited ability to move, to ingest food, to respond to certain external stimuli- could not, or at least not in a useful way.

The human social and technical systems we are concerned with in Problems of Scale are often highly complex and multidimensional. Indeed, one of the most important facets of scale problems in general is the introduction of complexity per se when scale has exceeded some limit. The problem with complexity is that it is hard or even impossible to predict all forms of behaviour- cognitive processing ability will always have some kinds of limits.

The principle of bounded rationality says simply that it is not possible to know everything about all but the most trivial of systems. There will always be suprises, always be aspects of behaviour which we could not predict. Bounded rationality is, in one sense, already conceded by reductionism- for if everything about a system were knowable then there would be no need to take it apart to understand it. The system as an ordered machine which the omniscient observer can perfectly comprehend has to give way to an altogether messier and less satisfying situation, in the same way that Classical physics has had to accept an ultimate bounding of its capabilities by the discovery of the Heisenberg Uncertainty Principle.

Given bounded rationality, one can only have an incomplete picture, or a partial perspective on a situation. It may be that there exist multiple perspectives, and therefore plural rationalities, just as the single Newtonian frame of reference has given way to the (infinitely) multiple frames of the Einsteinian Theory of Relativity. Newton's "Single Vision" is no longer adequate, and the commonsense view that there is more than one way of looking at everything is captured by the idea of multiple perspectives: different people may structure their perceptions of a situation in quite different ways. (Plural rationalities goes further, and says that different cognitive structural patterns arise consistently in particular ways and for particular reasons.) There is a very wide literature here; in management and OR mention should be made of Linstone (1984) and Mitroff (1983). An introduction to the plural rationalities program will be found in James, Tayler and Thompson (1987), and references therein. Heavyweight philosophical support for the general viewpoint is provided by Goodman (1978).

Anthropologists have long been familiar with structured partial representations of reality- they call them myths. A myth, in everyday usage, is something which is not true. On the contrary in this context, a myth is a story or a symbol which captures some essential partial truth. Jungian psychologists use a similar concept, that of archetypes. Applied to systems theory and management, we see myths and archetypes as convenient ways of explaining and communicating different aspects of the very complicated social, economic and technological problems which we encounter.

A lot of "Old Paradigm" thinking is concerned with the notion of optimality, particularly where numerical and mathematical analyses have been applied to complex systems. One or a few numerical measures of performance or desirability are to be maximised by manipulation of the system. However, even where this is possible in principle, the problems of bounded and plural rationalities make optimisation a very difficult objective to reach in practice. Firstly, it is difficult to optimise when uncertainty and restrictions on information mean that knowledge is so bounded that prediction of behaviour (and understanding of the behaviour of the system as it occurs) is problematical. Secondly, multiple perspectives may carry with them multiple optimisation criteria, and it may not be possible to satisfy them all simultaneously. (Arrow was awarded the Nobel Prize in economics for showing that, in general, it is not.) In many complex systems optimality may be a chimera, and its pursuit futile or counterproductive.

Complexity has been mentioned frequently above, and it is the attitude to complexity which lies at the heart of the alternative approach. The challenge is not to reduce it away, but to look it in the face, and accept the restrictions on knowledge and the ambiguities that it poses. An exploratory mode of investigation often has to be undertaken rather than a rigorously analytical one; archetypal models or "meta-models" are used to investigate selected aspects of a problem and to throw light on a particular chosen perspective.

Complex systems have other properties which contradict the single vision approach. The relationship between chance and determinism has been highlighted by some. The old view was of the system as a machine, in which behaviour was mechanistically predictable in theory (even if bounded rationality actually prevented it). Of course there are a great many things which are predictable in the world- we would not exist otherwise. However it appears that, contrary to what Einstein believed, God does play with dice, and just as some sub-atomic behaviour can only be described by a quantum theory which demands a high degree of indeterminacy, so chance can play an important role in the behaviour of many systems.

In particular it is not uncommon for a system to reach a bifurcation, where there is a choice between two stable paths of development. The choice may depend on very small events which are effectively random; once it has been taken the system continues deterministically along the selected path. An important consequence is that "history matters":

micro-level events can affect macro-structure, and the future development path depends on the past in a much deeper sense than in the "timeless" Newtonian celestial mechanics. (An introduction is given by Eigen and Winkler (1975). A more mathematical treatment is given by Arthur, Ermoliev and Paniovski (1986), whilst bifurcations in human systems are Erwin Laszlo's subject (1985).)

Perhaps the most crucial leap in understanding which has to be made is that away from the "commonsense" idea of equilibrium. Many things around us which have structure- plants and trees, animals, each other, the very atmosphere- appear to be in some sort of equilibrium. Yet this is an illusion wrought by the myth of single vision, which insists on seeing the world as a machine. Machines, our own creations, often are in equilibrium, but natural systems almost never are. The human body is a far-from-equilibrium system, both thermodynamically and chemically. It requires constant change, particularly a steady flow of air, water and food, to maintain its extraordinarily complex degree of <u>self-organisation</u>. The fact is that almost no interesting systems are equilibrium systems.

(The organic metaphor has been very popular with the General Systems movement, and does indeed offer a powerful dialectic to the systems-as-machines metaphor. However, the organic model is only one possible metaphor- the principle of multiple perspectives must still be applied¢ See Morgan (1986).)

Moreover, it is self-organisation combined with chance which permits the emergence of <u>evolution</u>. If the world is a machine we can extrapolate its behaviour into the future, and so too the lower-order system problems we are faced with more immediately. Machines do not evolve and their qualitative behaviour does not change. Real systems, organic or social, can evolve and their behaviour can go through transitions to different states. (See especially Jantsch (1980). On the phenomenon of self-organisation in biochemical systems see Nicolis and Prigogine (1977).)

5. THE THESIS

The problem facing the industrial planner is "How big should it be?" On the surface, this is a question to be answered by deploying various analytical tools, and by the judgement of seasoned practitioners. But analysis requires inputs and assumptions; in the case of scale decisions, assumptions about economies of scale, about changing technology, about the effects on the competitive environment of following particular courses of action.

The pre-analysis stage is less clear-cut but in some ways more significant: are there economies of scale? How can we be sure, and how accurately are they determined? If there are economies of scale, does this not imply that every industry will eventually be taken over by a single giant firm? If there aren't, what is the explanation for the historical processes which have led to the explosion in scale discussed in section 2? Why are there disagreements about the advantages of large scale?

The thesis is developed through the following argument:

In Chapter 2 the most important reductionist approach to scale is examined: that of conventional NeoClassical micro-economics, a fine example of the single-vision approach. Its development from the time of Adam Smith is traced forward to the work of Alfred Marshall, in which the theory of "increasing returns" (which include economies of scale and technological change) was essentially dynamic and organic. After Marshall, however, the twin demands of equilibrium analysis and the wish to construct mathematical models of microeconomic interactions led to the complete removal of increasing returns from the scene. The theory, which assumes perfect information for all actors, has become almost completely static, and is confined within the straightjacket of the U-shaped cost curve (another optimality construct).

The evidence supporting the theory is examined, and it is found to fail satisfactorily to account for the size and growth of firms and industries. It seems that more behavioural and evolutionary accounts of economic behaviour are needed- accounts which incorporate bounded rationality, and which allow for change and disequilibrium to a much greater degree. The traditional description of economies of scale is found to be deficient- for example, cost curves can be found which are not U-shaped at all. It is concluded that it is not easy to determine the existence of economies of scale in any particular situation, and still less to be confident of the optimal scale of plant or enterprise.

Furthermore, even if we assume that the existence of economies of scale is unproblematic, we have to consider the effects of the production unit's scale on its relationship with its environment- reducing the problem to the capital costs of the plant is not sufficient. A simple simulation model of dynamic diseconomies of scale is introduced in Chapter 3, which shows that the "optimal" scale of operation in a changing and uncertain world depends upon environmental context. This model abstracts the most important supply and demand features of a large-scale production situation, and shows how "common-sense" optimality notions are easily overturned.

In Chapter 4 the other aspect of increasing returns- technical change- is tackled. The principle of bounded rationality is applied to deduce some necessary conditions about the nature of technical change using Heiner's "Reliability Condition", which deals with how consistent intelligent behaviour should be in the face of uncertainty. Innovation is a search procedure with uncertain outcome (contrary to the NeoClassical assumptions). Search is constrained, and is guided by heuristics; the attempt to realise economies of large scale operation in production has been an important technological heuristic in the past.

The idea of technical change as a constrained search procedure is illustrated by a model in Chapter 5. Fictional production plants are successively built, with the aim of improving the production technology used and reducing the cost of output. In this model illustration the costs of output fall as more plants are built, in a fashion similar to the familiar "learning curve" phenomenon.

In Chapter 6 some fundamental disagreements about the optimal scale of operation in the electricity generation, brewing, papermaking and cement manufacturing industries are examined. It is argued that views about the "optimal" scale are often irreconcilable, being based on different premises and viewing "the facts" in very different ways. The theory of fourfold cultural bias from social anthropology sheds some very interesting light on these disputes.

Chapter 7 draws together all the elements of the argument. EMIR, an Evolutionary Model of Increasing Returns, attempts to overcome the limitations of the conventional economic approach to scale questions. EMIR is not a simple model, but represents an attempt to provide a better description of the behaviour and evolution of industries under conditions of increasing returns, innovation and incomplete knowledge. The model is described in detail in Chapter 8. Its findings, given in Chapter 9, include:

-that increasing returns are the norm and not the exception, and that EMIR shows that such complexities are not beyond the reach of investigation;

-predictions of the determinants of industry structure;

-predictions of the influences on the development of large- scale plants;

-an assessment of the merits and risks of pre-emption as a competitive strategy;

-that the competitiveness of an industry is not affected by the availability of technological economies of scale to the degree expected, but rather by other dynamic factors;

-that under conditions of increasing returns, market mechanisms cannot be relied upon to select optimal technologies or scale options.

In Chapter 10 EMIR is used to provide confirmation of Brian Arthur's thesis that important technological choices may be "locked-in" by the bifurcations of trivial random events. This application of the model is particularly interesting because it lies beyond the scope of conventional economic modelling methodology.

In Chapter 11 the conclusions are presented and the argument summarised. The implications are particularly drawn of the finding that market selection mechanisms cannot be relied upon to optimise. This has considerable consequences for decision-making in an uncertain world with room for plural views and in which there are increasing returns to scale.

The new systems approach deals in qualitatively different features, findings and modes of description from the classical scientific method.

Very complex problems must needs be approached in an exploratory manner, and the merits and demerits of the kinds of small models presented in the thesis are discussed. The exploratory approach is most appropriate to the pre-analysis stages of scale planning, where assumptions can be investigated and "worldview" scenarios experimented with.

Chapter 2: The Development of the Theory of Economies of Scale

> "There has lately been an increasing tendency to believe that the larger an organisation becomes, the greater the efficiency it almost automatically develops. Another view, perhaps slightly less widespread, is that for each industry there is one only optimum size of firm."
>
> Cadbury (1935)

> "Popular beliefs are seldom a safe guide in economics, and here they are especially suspect"
>
> Stigler, quoted in Teitel (1975)

"Economies of Scale" are often invoked as an argument in favour of bigness. The contention of this chapter is that, as a generalisation, the issue is much more complicated than it is often presented to be. The theory of economies of scale is traced from Adam Smith and before, whilst an account is given of the empirical research on the subject to the present day.

The microeconomic theory of scale has been subjected to a thorough critique by Gold (1981), and, as far as he goes, I have little to add. However I will use the subject matter to draw out some of the points of the preceding chapter, concerning the complexity of scale issues, the forces encouraging increases in scale, and the qualitatively different kinds of arguments used by the early theorists.

1. EARLY CONCEPTS- THE DIVISION OF LABOUR

1.1 Adam Smith

Many writers on "economies of scale" begin by referring to Adam Smith and his famous discussion of the division of labour in pin-making- so much so that it has almost become a cliche. In point of fact, the idea of improved efficiency through specialisation of tasks was not original to Smith; probably the earliest reference comes from Plato's "Republic":

> "Which would be better- that each should ply several trades, or that he should confine himself to his own? He should confine himself to his own. More is done, and done better and more easily when one man does one thing according to his

> capacity and at the right moment. We must not be surprised to find that articles are made better in big cities than in small. In small cities the same workman makes a bed, a door, a plough, a table, and often he builds a house too.... Now it is impossible that a workman who does so many things should be equally successful in all."
>
> (George, 1972)

A larger market permits greater specialisation, and thus yields potential benefits in the production process. Plato's laws stipulate that no craftsman be permitted to work in both wood and stone at the same time, because of the presumed loss of excellence this would entail.

As Routh (1975) points out, Adam Smith was not the first economist to set out the principles of division of labour; he was preceded by over a century by Sir William Petty (1623-87), who indeed originated many strands of modern economic theory.

> "... the gain which is made by Manufacturers, will be greater as the Manufacture itself is greater and better. For in so vast a City Manufacturers will beget one another, and each Manufacture will be divided into as many parts as possible, whereby the Work of each Artisan will be simple and easie."
>
> (Hull, 1899)

In "The Wealth of Nations" (Smith 1791; Jenkins 1948) Adam Smith was writing of a society being carried along by rapid industrialisation. It is surely significant that he begins his path-breaking treatise with the celebrated chapter on the division of labour, and indeed with the words:

> "The greatest improvements in the productive process of labour, as well as the skill, dexterity and judgement with which it is applied, seem to have been the effects of the division of labour."

The importance of this factor in economic growth is emphasised by the later remark that division of labour:

> "..is generally carried furthest in those countries which enjoy the highest degree of industry and improvement."

Smith analysed the manufacture of pins, and noted that it could be decomposed into about eighteen different operations. Whilst one workman "not educated to this business" would be hard pressed to make even one pin in a day, a small factory employing ten men could yield a daily output of about twelve pounds, or 4,800 pins per man. This vast improvement is due to three factors: the increase in skill and dexterity in each workman, who can more successfully master his specialised task; the saving of time previously lost transferring between operations; and thirdly "the invention of machinery which replaces hard labour and enables one man to do the work of many".

Thus the division of labour yields not only the static advantages of specialisation, but also dynamic advantages through (in modern parlance) "labour learning" and technological improvements via "learning by doing". Smith gives as an example of the latter the invention of the automatic regulator in early steam engines (although this story is probably apocryphal). It would be only a mild exaggeration to say that Adam Smith used "division" (of labour) as a verb in an active sense, denoting dynamic progress rather than a passive description of organisational or work structure. Certainly G B Richardson's (1975) interpretation of Smith suggests that his was an explicitly evolutionary economic theory.

Leijonhufvud (1986, p 210-12) makes the distinction between horizontal division of labour, i.e. Plato's craftsmen specialising in particular trades, and vertical division, as where Smith's pin-makes divide the sequential operations between themselves. The former is a question of minimum economical scale of operation, and often results in an increase in the worker's skill. The latter case economises on both capital inputs (since the same tools will be required as if only one were employed, with the difference that all will be used simultaneously) and labour inputs (since no worker needs to be proficient in all stages of the manufacture any more). Vertical division of labour therefore tends to be de-skilling and leads to increasing returns to scale of operations.

Smith's insights were further developed by the scientific talents of Charles Babbage (1832). The Lucasian Professor of Mathematics made detailed studies of work processes more than half a century before F W Taylor. He confirmed Smith's reasoning, and adduced a further principle yielding advantages for manufacture on a large enough scale to permit division of labour:

> ".. the master manufacturer, by dividing the work to be executed into different processes, each requiring different degrees of skill and force, can purchase exactly that precise quantity of both which is necessary for each process; whereas, if the whole work were executed by one workman, that person must possess sufficient strength to execute the most laborious of the operations into which the art is divided."

Specialisation allows more efficient utilisation of resources, particularly of labour, and Babbage estimated that this factor alone reduced the cost of manufacture of pins by a factor of three and three quarters. Babbage went on to consider the "Causes and Consequences of Large Factories", which include the use of "large capitals", i.e. machinery, better materials utilisation, and the possibilities of a kind of vertical integration, eliminating middlemen.

J S Mill (1832) contributed the idea that greater numbers gave possible advantages through cooperation and combination of labour. 'Simple' cooperation is demonstrated by the fact that two men can lift a weight which one cannot; 'complex' cooperation is Smith's division of labour. Mill considered the relative merits of manufacture on large and small scales, and noted that in England there was a rapid substitution of large for small establishments. Besides the technical causes, Mill saw also that the rise of the joint stock company was an influence in the growth of large scale manufacturing.

Others, for example Jevons and Wicksteed, added to and elaborated these concepts. However, I will pass over them to the beginning of truly modern economics, and to the person who could be considered its founder, the economist described by a later critic (Stigler, 1941) as "almost incomparably superior to his immediate predecessors and his early contemporaries": Alfred Marshall.

1.2 Alfred Marshall

Marshall continued the observational tradition of the early economists and, though a gifted mathematician, eschewed complex analytical techniques. His "Principles of Economics", first published in 1890, was clearly inspired by the success of Darwinism in the latter half of the century and, to quote Stigler again, "almost every subject in the 'Principles' receives its exposition in terms of evolutionary change". Stigler doubts the "expedience" of this, but on the contrary Marshall, in a preface to the eighth edition of his conceptually unchanged masterpiece (1920), says that "the Mecca of the economist lies in economic biology rather than in economic dynamics", and that, despite the frequent use of the word 'equilibrium', his work is "concerned throughout with the forces that cause movement". Despite his considerable contributions to equilibrium theory in economics, Marshall most certainly did not regard it as the be-all and end-all.

The evolutionary and dynamic nature of Marshall's thought is nowhere clearer than in his discussion of Industrial Organisation (Book IV of "Principles"). Marshall was fascinated by:

> "..the continuity in change of the living process in all its forms and phases and its effects on the structures and patterns of organisation- a great and badly neglected unifying thought- by means of evolutionary selection." (Foa, 1982)

His introduction to consideration of division of labour is concerned with setting out a "general rule" on organismic development "whether social or physical", involving increased subdivision of functions and increasing interconnection between them- in a sense anticipating Von Bertalanffy's "General Systems Theory" (1968), by more than sixty years. Specialisation of tasks led to increased skill and opportunities for mechanisation. Marshall saw that this in turn led to the creation of new kinds of jobs, some indeed integrating previously separate work functions (see e.g. his discussion of innovations in the printing industry, section 5, ch IX of Book IV). The potential for mechanisation meant that there was a tendency to increase the scale of manufactures, and this in turn meant that there was a further potential for division of labour of all kinds, "especially in the matter of business management".

It is clear that Marshall (and his predecessors) saw the advantages of scale as residing in the potential for task specialisation and improved work organisation, in the possibilities of using and 'inventing' specialised production equipment, in the acquisition of skill in the manufacturing process, and in certain other functional improvements- for example, Marshall describes how the large manufacturer may be able to afford extensive advertising and the employment of salesmen. "Economies of Scale" (a phrase not coined until the 1930s) do not derive automatically from sheer size, but from the potential for improvements in organisation and technology which size brings. In this respect Marshall is very 'modern', clearly recognising the distinction between 'science' and useful technology, and the importance of 'learning by doing':

> "Experiments on a laboratory scale or with small mechanical models have as a rule but little commercial value, until they have been fortified by practical proof of their

> efficiency on a working scale."
>
> "Industry and Trade" (1919) p 244

A sympathetic reading of "Industry and Trade" can even find evidence that Marshall recognised the existence of the modern theory of innovation and the product life cycle (Utterback and Abernathy 1975) in his discussion of the bicycle industry:

> "... when bicycles first came into vogue, every year brought some striking change in their construction and their methods of manufacture ... But now a cycle firm with adequate capital, administrative capacity and assiduity, can manufacture at a comparatively low cost for general consumption an ordinary cycle, that is immeasurably superior to those made by the first leaders of the industry ... Thus improvements in the methods and products of a partially standardised industry goes together with a certain decline in the place held in that industry by the high faculties of initiative: they are apt to be overshadowed by the more commonplace faculties of orderly administration and commercial skill; combined with large resources held perhaps in joint-stock ownership."

The Marshallian system distinguished between two sources of increasing returns- internal economies and external economies. The former are what are now known as 'economies of scale', whilst the latter derive from the effects of the scale of the industry as a whole, in terms of specialisation of tasks between firms, locational economies, and general synergistic effects- as exemplified by the growth of the engineering industries in the Birmingham area. This conceptual division was partly motivated by the need to explain why, if an industry were subject to "increasing returns", it did not become dominated by a single manufacturer. The existence of external economies could explain the continuation of competition under increasing returns. Marshall also resorted to arguing that the forces which led to the creation of large firms would enable new firms to quickly supplant them, due in part to the "decay of entrepreneurial faculties" as the original founders retired.

These kinds of defence became increasingly necessary during the 1920s. Ultimately they were judged to be inadequate as the Walrasian theory of price equilibrium put considerable strains on the notion of 'increasing returns'. Marshall died in 1924, and many of his most cherished ideas perished shortly afterwards (at any rate, they 'went underground' for a long time). The major casualties were Marshall's insistence on the importance of economic dynamics (despite his own substantial contributions to equilibrium theory), and his aversion to elaborate mathematical treatments of economic problems.

2. THEORETICAL CONFLICTS

Marshall provided a rich description of "increasing returns", in which scale change is clearly only one factor which cannot be separated from associated considerations of technological change, organisation of production and changes in factor inputs, i.e. changes in the proportions of labour and capital needed for manufacture at different levels of output.

("Increasing returns" means that marginal returns increase with scale. Thus static economies of scale are an example of increasing returns, since raising the scale of output reduces the cost of each unit of production, and raising scale still further reduces the cost of the extra (marginal) units of output further also. However "increasing returns" also covers a number of other economic effects, e.g. the modern "learning curve" phenomenon in which costs are often reduced with increases in cumulative output over time. Cumulative technological learning is a similar source of increasing returns. Arthur (1987) shows that there are often "increasing returns" to the adoption of new technologies, arising from learning effects (again); from informational factors (adoption is more likely as a technology becomes better-known); and through interrelatedness with other technologies or infrastructure.

Thus "increasing returns" covers a wide range of static and dynamic forces.)

Marshall set out his ideas in language which emphasised change and dynamics rather than equilibrium and statics. On the other hand, equilibrium theory demanded a very restrictive theory of scale changes, requiring no alterations in factor input proportions or in technology. Whether these conditions could ever be fulfilled, even in theory, will be discussed below; the fact is that they became the orthodoxy and have remained so until very recently. The reasons why this has happened, according to Gold (1981):

> ".. are not rooted in any demonstrably more effective insights into the advantages and disadvantages of larger scale operations, or the factors determining such results. Rather they have been motivated by placing a higher priority on integrating this sector of theory into the larger framework of production and distribution theory."

But this is to run slightly ahead of the developments. The 'cost controversies' of the 1920s saw the beginnings of the undermining of Marshall. John Clapham (1922a) in the so-called 'empty boxes' debate attacked the utility of the concept of 'increasing returns', pointing out that:

> ".. we do not, for instance, know under what conditions of return coal or boots are being produced".

He inquired whether any of the 'Great Analytics' could indeed determine the answer. He argued that the restrictive definition of scale changes should be avoided on the grounds that:

> ".. we never can know what proportion of ... efficiency is due to organisation resulting from mere size and what to invention."

(That problem still dogs the economic theory of scale economies). Clapham's elegant and witty assault was answered by Pigou's (1922) equally amusing intervention on behalf of the growing body of 'Analytics'. However, Clapham's claim about the inseparability of technological effects was not refuted in the subsequent melee (Clapham 1922b, Robertson 1924). Nor was Marshall's point about changes in factor proportions effectively countered:

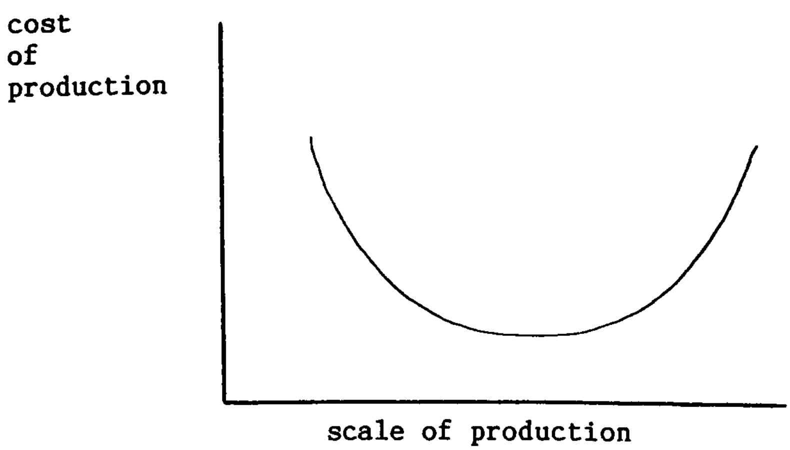
> "The quantities cannot be taken out exactly, because changing methods of production call for machinery, and for unskilled and skilled labour of new kinds and in new proportions."
>
> ("Principles" Book IV Ch 13)

Indeed, at the same time that this theoretical dispute was beginning to erupt, the observational approach, in the shape of the work of J M Clark (1923), was providing additional support for Marshall. Clark both emphasised the importance of invention and research as a specialised function in its own right carrying advantages for the entrepreneur large enough to sustain it, and also pointed to the possible physical economies of large mechanical units. Kotany (1922) provided an analysis of such effects (Clark drew on empirical observations from the US railway industry) by setting out elementary geometric justifications for improved efficiency from larger machinery- for example, that heat loss from a large steam engine should be less than that from a small engine because of the greater proportionate volume enclosed by a given surface area. Crude as these arguments are (and both Clark and Kotany were careful to point out that such geometric relationships are invariably subject to limits on their range of applicability), they nevertheless set up formidable obstacles to explaining how factor proportions could always be maintained in scale changes, when an important source of increasing returns was the supposed capital-saving possibilities of larger equipment.

But there were telling arguments on the side of the Analytics too. In particular, Marshall's explanation of the co-existence of competition and increasing returns was found seriously wanting, and the notion of 'external economies' was criticised. A telling blow was landed by Piero Sraffa (1926) attacking the logical consistency of the external economies idea. Stigler (1941) argues that Marshall failed to satisfactorily account for the continuation of competition in a (supposedly) equilibrium framework, correctly pointing out that the evidence on the 'decay of entrepreneurial faculties' which, Marshall held, would cause large firms to fail through atrophy of the competitive spirit before they grew to dominate the market, was very much against him (Steindl, 1945, adds weight to this case). Stigler also criticised him for logical inconsistency in failing to adhere to the doctrine of fixed factor proportions. Marshall was, in the view of the Analytics, too imprecise to fit properly into their theoretical framework (Viner 1931).

There was a further difficulty, which lay in Marshall's fixation on economies and neglect of diseconomies of scale. Equilibrium theory needed the existence of a U-shaped long run cost curve; in other words, there must be decreasing returns past some optimum scale of production:

Fig 2.1: The U-Shaped Cost Curve



A rearguard action was fought by Allyn Young (1928) on behalf of the recently deceased Marshall. Where Sraffa had sought a way out of the problem of competition by asking economists to abandon the assumption of perfect competition, Young set out a bold statement in favour of a dynamic economics, arguing that:

> ".. the counter forces which are continually defeating the forces which make for economic equilibrium are more pervasive and deeply rooted in the constitution of the modern economic system than we commonly realise."

The counters to equilibrium were changes in the organisation of production and cumulative technological progress. Young fashioned a redefinition of 'external economies', removing them to the industry level, away from individual industrial environments, and emphasising dynamic productivity growth. He took Adam Smith's theorem that "the division of labour is limited by the extent of the market" and argued that the reverse was also true, that the extent of the market depended in part on the division of labour. Thus a process of disequilibrating feedback produced increasing returns. It is striking, as Blitch (1983) points out, that there is no place for increasing returns in modern competition theory, when historical industry studies stress their role, and economic historians regard them "as a major factor in the industrial development of Britain and the United States". That is, historical and observational study suggests that innovation, division of labour and specialisation, and the realisation of economies of scale all play a crucial role in the evolution of modern industries and economies. Traditional economic accounts cannot or will not incorporate these elements and resort instead to arguments based on shifts in factor prices.

I have gone into this question before launching into the main subject-matter because I wished to show that neither Marshall's observational insights nor the instinctive desire for a dynamic economic framework which he shared with Young were refuted. Rather, certain other elements of Marshall's formalisations were found lacking, either through inadequacies in explaining actual competitive behaviour, or inconsistencies with the rigour of equilibrium price theory. This theory was in the 1920s a strapping youth, generally regarded as a great success. Young was ignored, partly for these reasons, partly because of his unfortunate early death, and partly, as his pupil and notable intellectual supporter, Nicholas Kaldor puts it, because his paper was:

> ".. so many years ahead of its time that the progress of economic thought has passed it by ... Economists ceased to take any notice of it long before they were able to grasp its full revolutionary implications."
>
> (Kaldor 1972)

Young's argument was not appreciated because equilibrium theory itself was not sufficiently understood. General equilibrium theory, Kaldor says, cannot cope satisfactorily with technological progress, and he goes on to say (1972) that:

> ".. it is evident that the co-existence of increasing returns and competition- emphasised by Young and also by Marx, but wholly excluded by the axiomatic framework of Walrasian economics- is a very prominent feature of de-centralised economic systems but the manner of functioning of which is still a largely uncharted territory for the economist."

Until very recently Kaldor himself has been relatively isolated, with only occasional contributions on the "neo-Marshallian" side (see perhaps Jones 1933, Wiles 1952, Balassa 1961). Fifty years on, there are signs of a resurgence in evolutionary economic thinking, represented by Richard Nelson and Sidney Winter (1982), fighting under the banner of Joseph Schumpeter, and by the "neo-Austrian" school (Kirzner 1982, Shand 1984). Until Marshall, "increasing returns" had a place in the thinking of every major political economist, along with and tied up in concepts of technological change, in the most central theories of economic progress. That place was denied upon the death (literal and metaphorical) of Alfred Marshall, and it remains to be seen whether it can be restored.

This is not to say that the restrictions imposed by equilibrium theory are due to the ignorance or stupidity of economists; obviously not. It seems to me that they are due to the methodology, to the kinds of models and tools employed by the Analytics, in this case the method of static equilibrium analysis, for:

> "the axioms of equilibrium theory were originally chosen in order to secure the desired result ... its authors were motivated by the belief that they were only laying the foundations of an explanation of how a market economy works, an initial stage of the analysis which is in the nature of 'scaffolding': it has to be erected before the permanent building can be built, but will be removed step by step as the permanent building nears completion. However, since Walras just wrote down his system of equations over 100 years ago, progress has definitely been backwards not forwards, in the sense that the present set of axioms are far more restrictive than those of the original Walrasian model."
>
> Kaldor (1985)

There has been a preoccupation with mathematical formalism at the expense of empirical verification; a recent authoritative survey concluded that:

> "The 'equilibrium' story is one in which empirical work, ideas of facts and falsifications, played no role at all."
>
> Weintraub (1983)

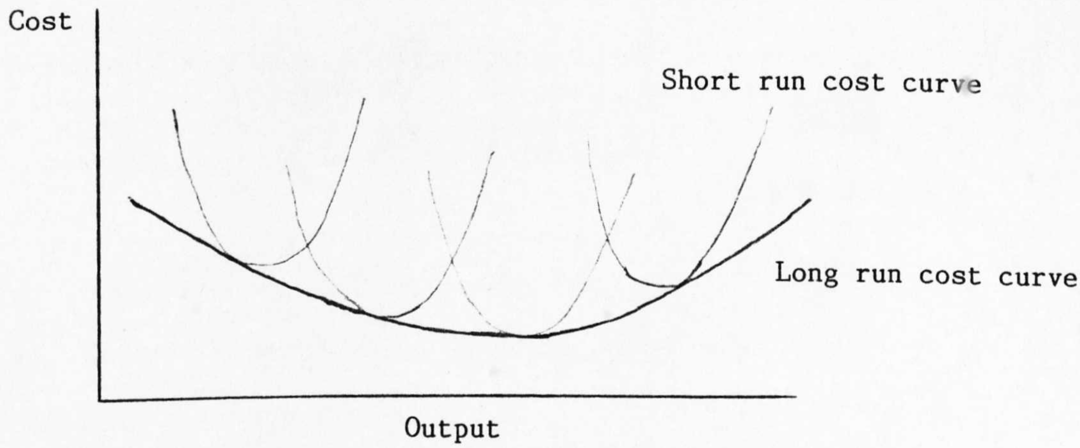
3. TEXTBOOK THEORY

3.1 The Cost Curve

The classic formalisation of economies of scale in equilibrium theory was provided by Jacob Viner's (1931) "long-run cost curve". The short-run cost curve was defined as the relation between cost and volume of output not allowing for any change in the scale of plant, whilst the long-run curve was the envelope of all the possible short-run curves (i.e. all those curves attainable by building plants of different sizes). The 'long-run' was:

> ".. long enough to permit each producer to make such technologically possible changes in the scale of his plant as he desires."

Figure 3.1.1: The Long Run Cost Curve



It was assumed that the LRCC would be U-shaped or more precisely, this was deduced from the 'laws of return'. To be fair to Viner, he pointed out that the shape of the curve would be an 'empirical question', but the assumption of an optimum size beyond which increases in the scale of the enterprise would yield decreasing returns was crucial to equilibrium theory. This assumption, as noted above, explained the possibility of maintaining several competitors in a given industry situation.

Some of the more subtle implications of this formalisation are analysed by Gold (1981); I shall only mention the starker ones. The assumption of fixed factor proportions is maintained. There is also an assumption of no substantial technical change, despite the rather misleading term "long-run". As Pratten (1971) notes, there is an inherent assumption of 'given' technological knowledge, and, as is to be expected in a neoclassical framework, the entrepreneur chooses the scale of production on the basis of perfect knowledge of the results, thus obtaining minimum cost for the output desired.

However, Clifford Pratten's detailed studies of the sources of technical economies of scale led him to the contrary conclusion that assumptions of given technical knowledge are "difficult to sustain in practice", and indeed that:

> ".. it is no longer always possible in practice, to isolate the economies of scale and economies attributable to technical progress ... It is therefore vitally important to consider the relationship between scale and change, otherwise we should be considering the effects of scale in a 'Canute economy', a fruitless exercise."
>
> (Pratten (1971)

Yet this is exactly what has happened; Huettner (1974) observes that "no diagram, chart or graph ever depicted more than one LRAC curve". Economists have always forced the data to fit on one curve (Huettner 1973). As an example of this, Huettner reviews cost studies in the electricity generation industry (Johnston 1960, Lomax 1952, Olson 1970) and shows how they have imposed upon the same cost curve plants of different vintages and technologies. Thus changes in technology have been ignored, suggesting that the effects of technical change may have been misrepresented as scale economies.

I will examine the 'empirical question' of whether the LRCC is in fact U-shaped presently, but at this point the sheer austerity of the 'orthodox' formulation should be pointed out. Not only is technical change barred, but there is really no convincing explanation attached to the neoclassical concept to show where the economies of larger scale production (if any) might come from. The best we get is F H Knight's (1921) statement that:

> "The fact of limited divisibility is responsible for all differences in the economies of operation of establishments of different sizes."

Limited divisibility of factor inputs becomes a catchall. Not merely are "indivisibilities" such things as one-off overheads due to set-up costs (largely effects on the short-run curve in any case), but in fact any improvement due to changes in organisation or utilisation of equipment. Thus the introduction of a completely new production process at a large scale of output, which would be uneconomic at lower outputs, would come under this heading. The analytical value of "indivisibilities" in this sense is practically zero. In a famous series of exchanges Edward Chamberlin denounced this usage of "indivisibilities" as tautologous (1948). The discussion, conducted in the pages of the Quarterly Journal of Economics, got into rather a tangle on the questions of what constitutes a tautology, and whether it has a use, and what can legitimately be called a factor input (McCleod and Hahn 1949, Chamberlin 1949).

Chamberlin argued that specialisation of function could not be reduced purely to "indivisibilities", and pointed out that if more "co-ordination" were needed to maintain larger units then the unchanged factor proportions condition would simply lead to dis-economies of scale, assuming that 'management' was to be considered a factor input. Chamberlin got the better of the argument, and Leibenstein (1955) showed that the assumption that perfect divisibility of factor inputs would eliminate economies of scale was quite incorrect. There could still be 'indivisible activities', yielding genuine economies. Kaldor (1972) (who opposed him at the time) admitted much later that Chamberlin had been correct. Schwartzmann (1958) summarised the verdict on Knight's definition:

> "The consequence has been a meaningless theory. It provides no generalisations concerning sources of varying returns."

As Gold (1981) points out, Stigler revised the early edition of his "Theory of Price" to say (1952) that "examples of technological indivisibilities are relatively rare ... In the great majority of cases, then, a productive service is capable of continuous physical variation".

Gold further highlights the fact that, although Pratten (1971) considers indivisibilities in his important empirical surveys of economies of scale, he provides only a theoretical discussion unsupported by concrete technical examples.

3.2 Explanations of Scale Economies

These weaknesses, as Schwartzmann says, do not mean that we have no theory of economies of scale. On the contrary:

> "The theory consists of the generalisations pertaining to the advantages of specialisation, of certain technological processes such as assembly lines on stamping machines, and the problems of managing large enterprises. Were these Marshallian categories emphasised rather than 'indivisibility' the methodological problems which have been examined here would not have arisen."
>
> Schwartzmann (1958)

Away from the straitjacket imposed by equilibrium theory these factors had not been ignored or completely devalued; for example Stigler (1951) claims that:

> "The division of labour is not a quaint practice of eighteenth-century pin factories; it is a fundamental principle of economic organisation."

By 1930 an additional source of economies was receiving increasing attention, namely the possibilities of greater proportional output from larger machinery and equipment. This shift of emphasis towards laws of 'increased dimensions' and away from 'division of labour', which has been sustained throughout the twentieth century, is due at least in part to the increase of what Gold (1979) calls 'capital-dominated' and the decline of 'labour-dominated' industries and processes. (Blaug (1963) shows that it was not until the end of the nineteenth century that the 'myth' that technical change had a necessarily labour-saving rather than capital-saving bias was exploded). That is, whilst in Adam Smith's day it was more often the case that output was limited by the quantity and quality of labour that could be organised for production, today the limiting factor is usually the capital stock deployed- the addition of extra labour results in little or no increase in the output or efficiency of a modern petrochemicals plant or steelworks, for example. Boulding (1941) introduced allometric arguments to explain why different sizes of equipment give different proportionate outputs:

> ".. a flea can jump over a scale model of the Capitol, scaled down to the size of a flea. If a flea were as big as a man, however, it could not jump at all. Its legs would break. This is due to the fact that the strength of muscles and bones is proportional to their cross-section, which is an area. The weight of an object is proportional to its volume .."

Boulding suggests analogies with business enterprises and organisations. (See also Naroll and Von Bertalanffy (1956)). Care must be exercised with these kinds of argument- as will be shown below in the discussion of the evidence for the so-called "six-tenths rule". However, there is no doubt that these kinds of relationship do yield genuinely varying returns to scale, and indeed they are probably now the most frequently cited source of scale economies.

To return to the U-shaped cost curve again- where is the relevant evidence? At the same time that Viner was working out the theory, Robinson (1931) was developing a detailed argument to show where decreasing and increasing returns at the level of the individual firm came from. Many of the propositions Robinson advanced are frequently still repeated, so it is worth enumerating them.

In keeping with the spirit of contemporary theory, Robinson talked of the "optimum" size of firm, although he did not allow himself to be hedged in by theoretical restrictions to a serious extent. On the side of the advantages of scale, the usual discussion of pin factories is enhanced by reference to the production line for the Model T Ford- 7,882 operations, according to Henry Ford- and to the 'Integration of Processes' by machines. The 'Economy of the Large Machine' resides in the geometric relationships alluded to above, and to the fact that a large firm can supply sufficient work to keep big and expensive equipment occupied. For the same reasons the large firm is better able to maintain the efficient balance of processes between successive stages of production. Further economies are derived from massed reserves (inventories of spare parts) and standardisation of components.

There are also potential economies of large scale organisation, Robinson believes, through specialisation of managerial functions (e.g. personnel, market research). Larger firms are believed to find it easier to raise capital, and to gain better terms in their materials purchasing. Similarly, the possibility of affording large-scale advertising and marketing personnel, combined with more rapid stock turnover and potential for great product range are advantages of selling on a large scale.

If there are technical diseconomies of large scale production then, given the neoclassical assumption that we realise that they exist, they can be avoided by building multiple small units of plant (this point was noted by Viner at the very outset). Therefore, any sources of decreasing returns must be due to diseconomies of large-scale management, and indeed these are the limits to scale Robinson discusses. Problems of coordination, loss of flexibility, and the dangers of bureaucracy are outlined in some detail. The advantage of small decision-making units is stressed, and there is mention of the problem of motivating workers (and managers) in the large firm.

However, and this will be a recurring cry, Robinson felt that far too little attention had been paid to empirical studies of the variation of returns with size:

> ".. we know far less than we ought to know about the extent of the economies of scale. How much does a firm's cost of production increase if it is, say, 25 per cent below the optimum size? Is it a matter of 2.5 per cent? Is it a matter of 10 per cent?"

3.3 Lack of Empirical Evidence

Little substantial progress was made in answering these kinds of questions for some time. Thus Blair (1948) remarks that:

> ".. it is a matter of amazement that so little effort has been directed toward examining this fundamental problem in the light of factual data .... The explorer in this field stands, indeed, on barren ground."

And, again, a survey of the evidence by Caleb Smith (1955) produces the finding that:

> "Based on the survey, the conclusion is that the generalisation that available empirical information supports are (sic) indefinite and disappointing."

Walters (1963) found that the existence of economies of scale was 'only clearly established for public utilities', and concluded that there was insufficient evidence to decide whether long-run cost curves were U-shaped or not.

Thus it was that on the one hand Smith could conclude that:

> ".. there is no substantial evidence that the long-run cost function for plants does not continue to decline up to the largest sizes found in practice."

whilst others could continue to hold to the view that long-run cost curves were U-shaped- for example a note by Viner (1950) asserted that:

> "I know of no convincing evidence that the optimum-efficiency size ... is not quite moderate for any industry of any appreciable size."

What evidence there was seemed to rest against the U-shaped cost curve; a report by the US National Bureau of Economic Research (1943) showed an L-shaped cost function for all but one (grocery retailing) of eight industries considered, and studies reviewed by Moore (1959) suggested a similar conclusion in the majority of cases. Wiles (1952) argued ferociously against the dominant orthodoxy on technical knowledge as well as against U-shaped cost curves, which he ascribed to "a confused and naive belief in the diseconomies of large management". He threatened the "wreckage of general equilibrium theory" ("it is all in Marshall " he exclaims in a footnote) and asserted that:

> "The conclusion appears inescapable: the doctrine of the optimum size of the firm must be abolished; it is quite wrong."

Wiles provided considerable evidence, in the shape of empirical cost curves for both plants and firms, to support his position. He is surprisingly rarely cited- perhaps because of his theoretical heresies.

On the other side of the argument, J M Blair (1948) produced a number of sets of figures showing that total firm costs of production were U-shaped for Bakeries, Rubber Tire manufacture, and the production of mixed fertilisers and superphosphates. All these early studies tended to be of variable quality; for example one of those reviewed by Moore (1959) included 15 estimates of scale economies by the Harvard Economic Research Project. Of these 15, 8 relied upon only 2 plants, 2 on 3, 2 on 4, 1 on 5 and 2 on 6; with such paucity of data, standard errors of cost estimates must be very high.

Hindsight, benefiting from the studies carried out once the lacunae in empirical studies were realised, enables us to conclude that in fact long-run cost curves at the plant level are generally L-shaped rather than U-shaped. (See in particular the Cambridge University studies: Pratten and Dean (1965), Pratten (1971), Silbertson (1972), and the international comparison work of Scherer et al (1975) and discussion below).

3.4 Criticisms of the Cost Curve

Before considering the general body of the studies of economies of scale, however, some wider points are in order. Firstly, the assumption that the long-run cost curve is smooth (whatever its overall form) is not always or necessarily true. Moore (1959) points out that the curve may be 'scalloped' due to the very fact that the fixed factor proportions condition is rarely fulfilled in practice:

> "Among other reasons, economies of scale arise because the proportions among inputs change as scale of plants change ... In other words, the 'scale line' may have 'kinks' in it as the size of the plant expands."

This means that, even if the curve is basically L-shaped it may contain more than one point of 'minimum' cost- as was indeed found by Scherer et al (1975) in the case of the manufacture of paint and of batteries. This resulted in the coexistence of small and large plants, medium-sized plants either tending to disappear or "leap forward to larger and more efficient scale". Similar possibilities have been explored by Alan Bollard (1983) for the brewing, cheese-making, waste-paper and plastics recycling, brick-making and other industries. A wide range of factors, including different technologies, transport and marketing costs, and product differentiation, lead to wildly varying concerns having broadly similar costs of production- but for very different reasons.

A second underlying assumption of the cost curve is that it relates to a planned output of only one product. In reality this situation is very rare; even 'flow' production processes such as chemicals manufacture usually have a range of possible product mixes from the same equipment. Cockerill's study of the international steel industry (1974) found that:

> ".. the minimum efficient scale of plant for the manufacture of steel products depends both upon the process by which the crude steel is produced and upon the product mix of the final total output. Hence we may expect several output scales to be optimal according to the technical and market factors assumed."

Thirdly, there is the idea that the existence of a minimum cost point is sufficient to establish the existence of an optimal scale of operations. This is equivalent to stating that the entrepreneur's objective is to minimise costs. When economic theory directly addresses the question, however, it is generally recognised that the objective is to maximise profits, and that the two things are by no means equivalent. Thus the minimum cost point may not represent the 'optimum' size of enterprise.

These considerations demonstrate that, even to the extent that the traditional cost curve can be held to be a reasonable approximation to the real world, it is, as Jewkes (1968) puts it:

> ".. a great gap in logic and a vast misunderstanding of the dynamics of industry, to suppose that there is one optimum size of firm and that the only thing that matters is the size of the biggest firms."

Yet, according to Gold (1981), this assumption that there is some optimal size of production, is about all that is left of the "traditional approach" to the theory of scale economies. It may be felt that I have to some extent set up straw men to attack in this discussion of the "traditional approach". This is true, in as much as increasing numbers of researchers dealing with the empirical evaluation of economies of scale have been adapting and abandoning many of the theoretical restrictions and simplifications placed upon them by the 'Analytics'. To that extent the published literature on economies of scale has become far more sophisticated and less hidebound in the last quarter century.

The Analytics are also attempting to come to grips with the difficulties which increasing returns to scale present for the competitive equilibrium. The theory of 'Contestable Markets' takes account of the multiproduct firm and allows for the existence of flat-bottomed, as opposed to U-shaped, long run cost curves (Baumol, Panzar and Willig, 1982; Baumol and Braunstein, 1977). This does at last seem to be an attempt to remove some of the 'scaffolding'. At the risk of seeming churlish, however, it must be said that Marshall would not have approved - Baumol et al still have both feet planted in the furrows of equilibrium analysis, ignoring possibilities of evolutionary change. Moreover, the whole is accomplished with the aid of chapter after chapter of mathematical equations of quite baroque abstraction.

There is no clear alternative to the theory which emerged sixty years ago, despite the accumulation of evidence of weaknesses in that theory. To some 'Analytics', indeed, it would seem that nothing has changed- for example, the eleventh edition of Samuelson's "Economics" (1980) still maintains the requirement of fixed factor proportions. Lipsey's 'Positive Economics' (1979) professes a more empiricist route than many economic textbooks, and yet still retains the U-shaped cost curve for both plant and firm- although it now goes so far as to admit that this is merely an assumption for the latter. I have yet to find an introductory text which does not feature the U-shaped long run cost curve, usually in the form of a diagram, nor yet one which can bring itself to the point of confessing the extent to which empirical investigations disprove the assumption. Moreover, the U-shaped cost curve assumption has spilled out into other areas, e.g. introductory texts in Production Operations Management. It would not be totally out of place to recall Piero Sraffa's "famous criticism" (1926)- and apply it to the theory that was victorious half a century ago:

> "That its foundations are less solid than those of the other portions of the structure is generally recognised. That they are actually so weak as to be unable to support the weight imposed upon them is a doubt which slumbers beneath the consciousness of many, but which most succeed in silently suppressing. From time to time someone is unable any longer to resist the pressure of his doubts and

> expresses them openly; then, in order to prevent the scandal spreading, he is promptly silenced, frequently with some concessions and partial admission of his objections, which, naturally, the theory had implicitly taken into account."

4. EMPIRICAL STUDIES

4.1 Bain and Other Pioneers

Thus, even after the Second World War there were serious shortcomings in the theory of returns to scale, both conceptually and in the lack of supporting evidence. As we have seen, the situation was such that economists could choose the facts to suit whatever policy prescription they chose. Bain (1956) remarked on the fact, that, whilst American economists were writing in support of open competition and anti-monopoly positions, their British colleagues, particularly Robinson, Florence and Steindl, were taking the opposite stance:

> "These British writers are much more likely to be concerned with explaining the failure of firms in unconcentrated industries to take advantage of the allegedly manifest advantages of very large-scale operations (citing deficiencies of capital markets and the like) than with documenting their assertions relative to the supposed advantages of large scale."

Bain himself was one of the pioneers of sound empirical research in the field. His methodology for cost estimation was based on the use of questionnaires for managers and engineers in each of the industries studied, backed up from other diverse sources- for example trade journals. His study of about 20 industries in the USA (1956) was intended for the analysis of competition and the so-called "barriers to entry" that the existence of scale economies are believed to impose in certain industries. Bain was therefore most concerned with the evaluation of minimum efficient scale (normally abbreviated to m.e.s.). This is variously defined by different researchers; the most widely accepted definition is Pratten's (1971), that m.e.s. is the size at which any subsequent doubling of plant scale would yield further cost reduction of no more than 5%. Bain found that m.e.s. was generally a small share of the industry (in the US¢) and that the economies of multi-plant operation were slight (a detailed discussion of the presumed sources of and evidence for multi-plant economies will follow later in this chapter).

Some observations on methodology would be appropriate. It was soon realised that firm's accounting data, even where they provided ostensibly relevant information, were misleading for comparative purposes. Firms may deliberately under- or over-capitalise for a variety of reasons- construction cost overshoots or other mistakes may be hidden in this way, for example. In particular there are certain sectors, like the electricity supply industry in the USA, where it is advantageous to over-capitalise because pricing policy is based upon rate of return on capital. Furthermore, because professional accounting bodies do not generally impose strict comparability controls on cost accounts, comparisons between companies, or even between plants of the same company, or between costs of production at the same plant at different times, are hazardous to say the least. The best one could do is hope that there were no systematic biases related to plant scale or firm size- yet it is not hard to think of reasons why there might be, particularly in industries with only very few companies (see also Huettner, 1974).

4.2 Estimating Scale Economies

The questionnaire or "engineering estimate" method, including interviews and searches of published materials, is generally accepted as the most reliable means for estimating cost curves for plants and for whole companies. Given a reasonable number of independent estimates this can be quite an effective method, although it too is subject to certain problems. For policy-making the most critical situation requiring an estimate of m.e.s. is often the case where monopoly or near-monopoly holds- and here there may be only one or two estimates. Moreover, there is, as Gold (1981) remarks, a tendency to regard the present largest size as optimal:

> ".. compare the minimal estimates of the prospective gains from scale and technological improvements in the US steel industry .. and the long continued insistence of industry spokesmen that it is technologically equal to the best, with estimates of the superior performance levels already achieved by the major Japanese steel mills (Gold, 1979)."

Whilst the method might be good for determining costs of plants within the current size range, beyond that range it may be much less reliable. Estimates may be strongly influenced by the conservatism or the optimism of managerial expectations. The m.e.s. turns out to be equal to the largest current plant with striking frequency. There is perhaps some justification for this, as often particular technical problems have to be solved before plant scale-up can be achieved. In a sense one can only claim what has been actually tried out in practice as 'state of the art' technology. Put this way, it is clear that untried possibilities cannot be fairly accounted for. A critical theorist could reasonably object that the method therefore amounts to no more than well-informed guesswork, possibly biased by management's future intentions.

The most notable studies of this kind have been by Bain (above), by Pratten's group at Cambridge (Pratten and Dean, 1965; Pratten, 1971; summarised by Silbertson, 1972) who examined 25 UK industries, and by Scherer et al (1975), who studied 12 selected industries in the US, UK, France, W Germany, Italy and Sweden. These studies include analysis of the relevant industry structure, and a careful discussion of the sources of economies cited by interviewers and found in the literature, as well as numerical cost estimates. These wide-ranging and thorough studies constitute the best body of knowledge on the existence of economies of scale. They confirm that long-run cost curves are largely L-shaped, at least at the plant level. Precise estimates of the degree of economies available and the sensitivity of m.e.s. estimation to errors are slightly less reliable (Gorecki, 1978). Comparing successive studies suggests that m.e.s. increased rapidly in many industries during the 1960s; therefore it would be unwise to assume that either Pratten's or Scherer's estimates are still applicable.

A large number of other studies, usually concentrating on one industry in each case, have been carried out in the last twenty years using essentially similar methods of data collection. These are reviewed below under various headings of industry group and method of analysis. Other wider ranging studies worthy of mention here are those of Huettner (1974) on electricity generation, cement making and steel, and the collection of estimates from UN sources by Teitel (1975). This paper also contains an excellent summary of other published research.

Besides 'engineering estimates', there have been two other strategies employed for examining scale economies, both relying on data provided from national industry censuses such as the US Census of Manufactures. These data sources give various sorts of information about employment, value of output, certain costs, and capitalisation (varying between sources). This information is divided up according to the Standard Industry Classification (SIC) at varying levels of aggregation, known as the two-, three- or four-digit SIC codes. A study at the two-digit level will typically divide the US economy into some twenty or thirty sectors; at the four-digit level there may be three or four hundred classes. Within each sector firms will be grouped according to employment or output in size classes to preserve confidentiality, although full firm or plant size data sometimes becomes available.

4.3 The Survivor Test

One application of this data has been in the so-called 'Survivor Technique', pioneered by Stigler (1958). (Saving (1961) credits J S Mill with the idea, but I haven't found any evidence of this.) Stigler argues that the determinants of the optimum size of plant or firm (he considers both) are so complex that an analytical approach based on questionnaires must be permanently handicapped, in particular because of the subjective nature of the estimates obtained even when all relevant factors have been considered. Stigler attempts to cut the Gordian knot by arguing that, if one size of plant has cost advantages over another, then if we compare observed industry size distributions over time we will see a shift towards the 'optimum' size and away from sub-optimal scale. Such time-series comparisons thus provide an 'objective' evaluation of relative real costs in the actual environment with which the firm is faced.

The technique enjoyed a brief vogue, and Stigler's work was followed up by Saving (1961), Weiss (1964), and Shepherd (1967) in the US and by Rees (1973) in the UK. However it has fallen out of favour as a number of serious problems have been pointed out. In practice researchers were having to make judgements on optimality based upon shifts of fractions of a per cent of output between size classes in some industries, so that small trends could lead to freakish interpretations- size groups of little significance being declared 'optimal' whilst groups accounting for almost the whole of an industry's output were ignored. It was not always clear what the best performance measure was- relative or absolute changes in value-added, or value of shipments, or employment were all considered, leading to conflicting conclusions between studies. The well-established tendency for larger plants to be more capital intensive is a source of potential bias in the US studies, where the Census classifies size on the basis of employment.

Furthermore, misleading classifications lead to firms being incorrectly compared when they are not in the same business. Bain (1969) lists a range of factors which can account for the survival of small establishments, which include location factors, government subsidiaries, restrictive practices, factor prices varying across the country, and other.

Finally, even if all these methodological objections could be overcome, there are flaws in principle. There is the familiar point, as put by Shepherd (1967), that "survival may reflect higher revenues rather than lower costs". More than this, the 'survivor technique' produces results which are of small normative significance, for it is a serious error to assume that evolution 'optimises'. As Shepherd puts it, "What is, is not necessarily what ought to be". Although Gold (1981) still expresses an interest in the method, Shepherd (1967), (1979) and Bain (1968), (1969) have cast severe doubt on 'survival-ability', and it must be reported that the survivor technique has failed its own test.

4.4 Production Functions

The other main use of Census data has been the recurrent attempt to fit them to Cobb-Douglas or other production functions. Production function analysis has been the dominant means of tackling questions of increasing returns and other econometric problems in the last forty years. The production function has the advantage of relating input factor quantities to output quantities without needing cost data. Under certain fairly weak assumptions the existence and degree of economies of scale can be inferred from an estimated production function (Walters, 1960). The simplest and most widely-used formulation is due to Cobb and Douglas (1922 - see also review by Walters, (1963)), relating output (Q) to input factors, typically labour (L) and capital (K) by:

$$Q = k.K^{a1}.L^{a2}$$

where k is a constant related to the level of technology, and a1, a2 are the elasticities of output with respect to capital and labour inputs respectively. This is clearly a ruthless simplification; the most serious shortcoming is perhaps the imposition of the condition of homotheticity, i.e. that there are constant rates of change of returns at all outputs. Received wisdom suggests that economies of scale in fact decline after some scale of plant for any given state of technology, and the Cobb-Douglas formula does not allow for the exploration of this possibility.

In practice, this theoretical restriction has been matched by the same kinds of problems with the census data as handicap the survivor technique. Information on inputs is usually not in the form required, and some highly ingenious estimation methods have had to be devised to get the data into a usable state. More than this, however, there is the problem, as pointed out by Moroney (1972), that:

> "Individual manufacturing plants typically produce several commodities, and in this circumstance the very notion of a plant's homogenous physical output is a conceptual fantasy."

Further, a notable study of the US automobile industry which did take account of different product mixes found that scale economies and diseconomies varied substantially for different production possibilities, yielding paradoxical results when the data were forced into the more usual single-measure descriptions (Friedlander, Winston and Wang 1983).

Finally, there is the problem of aggregation- plants producing dissimilar products being lumped together even in the four-digit SIC classes, let alone the two-digit stratification more frequently employed. Given that recent single-industry studies have repeatedly shown the existence of different production functions for different production processes within the same industry, and have even suggested, contrary to the usual neoclassical assumptions, that these may vary between firms (see Joskow and Rose, 1985), this degree of aggregation presents serious problems.

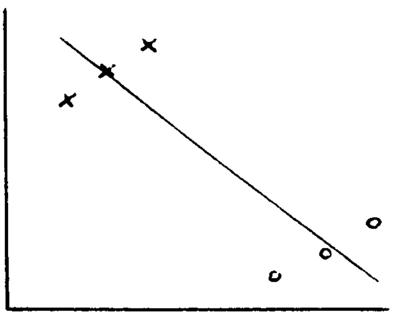
Nevertheless, a number of exercises of this kind have been carried out, by Murti and Sastri (1957), Yeh (1966) and Williams and Laumas (1984) on Indian data at an approximately two-digit level of aggregation; by Griliches and Ringstad (1971) for Norway; by Brown and Poplin (1962) on historical American data (1890-1956) and by Shan (1965) for the local Census of the Commonwealth (state) of Massachusetts; by Ferguson (1967), Hildebrand and Liu (1965) and Moroney (1972) on the US census of Manufactures at the two-digit level; and by Miller (1978a), (1978b) at the four-digit level on the same source.

The problems with these studies are exemplified by Moroney's (1972) comparison of his results with those of Ferguson (1967a) and Hildebrand and Liu (1965). The exponents for the eighteen different classes (examples: "chemicals", "Nonelectrical machinery", "Transportation equipment") are compared. In only one case do the three studies agree on the basic question of whether there actually are economies of scale, never mind the degree of any such economies. Griliches and Ringstad (1971) and Miller (1978a) are marginally more convincing with their more detailed breakdown, finding economies of scale in most sectors.

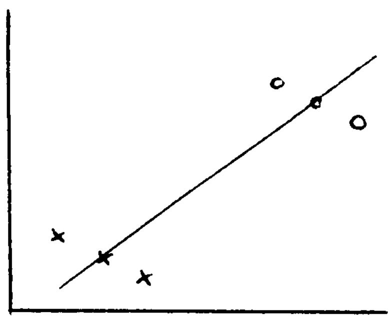
The problems of aggregation and mis-specification remain, however, and are blithely ignored by many researchers. Ferguson (1967a) finds some 'curiosa' in his results, and, although remarking that they could be explained by "assuming" the existence of two distinct technologies in some of the sectors, one being more capital-intensive and possessing greater economies of scale, he prefers to explain the aberrations in terms of demand and supply considerations.

The two figures below illustrate the possible effects of differing technologies on functional estimates. In Figure 4.4.1 (a) there are two distinct production technologies, each exhibiting increasing returns, yet showing decreasing returns when regression analysis is applied to the aggregate data. Figure 4.4.1 (b) shows the reverse case.

Figure 4.4.1: Estimation errors through aggregation



(a)



(b)

Finally, almost all of the above studies use the simple Cobb-Douglas production function. Williams and Laumas (1984) set out to test some of the assumptions behind the C-D by employing a more complex formulation, the translog production function (see Christensen, Jorgenson and Lau (1973) and applications: Lau and Tamura (1972) and Christensen and Greene (1975)). They found that "models based on a Cobb-Douglas production technology are inappropriate for all industries in India". By implication, they are probably inappropriate in many other cases.

It is difficult, therefore, to avoid the conclusion that these studies have been of little value, due to the quality and level of aggregation of the data, and because of mis-specification of the production function itself.

5. ENGINEERING STUDIES OF SCALE INCREASES

As remarked earlier, there has been a trend towards explanations of economies of scale based upon notions of the 'economies of Large Machines', as Robinson put it. Thus the most frequently-cited reference on economies of scale in the last fifteen years has been Haldi and Whitcomb's (1967) study of cost-scale relationships for various items of process equipment, based on geometric/allometric rationalisations. These have now taken the place of Adam Smith's pin factory as the ritual explanation of increasing returns to scale, and for that reason are worth an especially close examination.

5.1 Engineering Production Functions

The engineering approach was initiated by Hollis Chenery (1949) who proposed "a method by which engineering data may sometimes be used to approximate the production functions of economic theory in the industrial field". The production function was originally used for econometric analysis of national economies; Chenery used it to fit data on individual plants supplied from engineering estimates. This analysis led to the standard formulation of cost-output relations of the form:

$$y = KX^{A}$$

where y is the cost of plant, X its capacity, and K a constant. The exponent A is often quoted as 0.6 or 0.7, justified by the observation that this is the same as in the equation relating the surface area to the volume of vaguely spherical tanks or containers or other items of process plant. This exponent should strictly be 2/3, so the relation is variously known as the "2/3 power law", the "0.6 rule" or the "six-tenths power law".

The most widely-known studies in the economics literature are Bruni (1963) and Haldi and Whitcomb (1967). They attempted to fit the power-law to a wide range of items of process equipment, and found a wide range of exponents. In general, the median exponent for items of equipment was around 0.6, and for whole plants around 0.7, although little indication is given of confidence intervals.

A slightly earlier study by Moore (1959) had examined deductions of similar relationships from a range of war-time and other less well-known and unpublished sources on whole plant economies, and suggested, in view of the lack of statistical significance of much of the material, that "the results must be viewed with scepticism". This drew an interesting and revealing response from two engineers working in chemical economics, S Schuman and S Alpert (1960), who asserted that:

> "The fact is that in every case of our experience in the chemical and petroleum industries, large plants can be built at a lower unit cost than smaller ones."

The gist of their argument was that it was difficult to prove a rigorous mathematical relation between cost and output, but that they knew very well that the power law could be applied as an approximation. They gave a detailed cost breakdown of various items (pumps, valves, piping), required for water-pumping plant over an 'output' range of a factor of 1,000,000. A previous study by Alpert (1959) on the costs of metal milling machines was cited in support.

Moore, in a reply (1960) pointed out that the figures for the pumping equipment showed varying returns to scale at different points in the size range. He noted that there were:

> ".. diseconomies of scale in two areas (pumps and valves) for the largest scales of plant. Also the coefficient for total plant materials does not parallel closely any of the five major process areas. This means, of course, that these areas do not expand together in any regular way but rather that unbalanced expansions take place".

It should also be added that the Alpert (1959) estimates for milling equipment and lathes show a similar variation of rates of return at different scales. The impression is that, whilst the allometric relationships are in some sense true, they are seriously simplified by forcing them to fit a single (homothetic) cost equation.

5.2 The "0.6 Rule"

At the risk of labouring the point, reference to the engineering literature quoted by economists as a justification bears out this perception. Schweyer (1955) credits Williams (1947a), (1947b) with the original use of the "six-tenths law". Williams and Chilton (1949) collected a wide range of estimates for items of chemical engineering equipment such as pipes, drums, tanks, pumps, compressors, motors, and so on, and for 36 different types of complete chemical plants (Chilton, 1950). Again a very wide range of exponents was found both for items of equipment- 0.48 to 0.87 by Williams (1947a) and 0.33 to 1.02 by Chilton (1950)- and for whole plants. In addition, some log-log plots of cost vs performance began to curve up at the upper limits of size, showing declining 'economies of scale'.

The fragility of these relationships is illustrated by three separate estimates of the exponent for "tanks". Williams (1947a) finds the expected 0.59 (near two-thirds), but Williams (1947b) gets 0.48. Meanwhile Dickson (1947) finds an exponent of 0.70. A hasty intervention by the Editor of 'Chemical Engineering' reveals more complications without really explaining the differences in the estimates:

> ".. tanks will ordinarily increase in shell thickness with increase in diameter. This is necessary to maintain a constant unit stress in the shell material, since the unit stress in a thin cylinder is proportional to both the pressure and the diameter. Therefore the weight of the material will increase more rapidly than the increase in surface area and the cost might be expected to increase more rapidly than the 2/3 power of the ratio of volumes. Against this is the fact that the cost per pound of tank for fabrication, handling and installation decreases markedly as

the size increases ..."

Subsequent chemical engineering work confirms the impressions received from these studies. The numerous estimates of Aries and Newton (1955) show exponents rising at the top of the scale range, as do those of Guthrie (1970), who draws 'cost curves' for plant on very few observations for each type, producing exponents ranging from 0.38 to 0.83. Chase (1970) explains that non-linearities are quite frequent and that the six-tenths law is for quick, preliminary estimates only. Bauman (1964) repeats this warning, and cautions against extrapolation to unfamiliar processes or plant capacities. Matley (1984) repeats that cost lines will curve upwards at the limits.

Those economists who have looked for deviations from the simple cost-capacity equation seem to have found them- e.g. Walley and Robinson (1972), and Norman (1979), who found that the "0.6 rule" could only be used as a "local approximation" to the degrees of economies of scale in cement production. The message that the six-tenths power law, whilst representing a fundamental physical relationship, nevertheless hides considerably more than it explains, has unfortunately not penetrated to everyone yet- another recent study in a process industry tested for this relationship and commented that "the estimated coefficient (is) not significantly different from 0.6667" (McBride 1981). One wonders if the fact that 2/3 has no decimal expansion gave the author methodological problems.

6. DETAILED STUDIES AND NEW INSIGHTS

The introduction of engineering-based studies into the pursuit of scale economies, although leading to over-literal acceptance of what are only 'quick and dirty rules of thumb', has nevertheless led to a deepening of insight in many respects. In particular, it has led to a re-appraisal of what I will argue is an intimate link between scale change and technological progress. The addition of empirical studies of the technical sources of economies of scale and theories of technological progress have enriched current thinking on increasing returns, although this "neo-Marshallian" strand has not yet been woven into the fabric of modern economic orthodoxy.

6.1 Technical Change and Scale Change

To return to engineering production functions for a moment. Chenery's (1949) pioneering efforts attracted considerable attention among economists for a while, but this died down quickly because, as Pearl and Enos (1975) put it, "all but the simplest processes defied such exhaustive descriptions" i.e. the decomposition of all elements in terms of a single performance equation. However, this formulation did provide a means of measuring technological progress and evaluating its direction and results, as Pearl and Enos demonstrate. Chenery himself provided useful insights into technological change in pipeline transportation, showing how increases in working stresses and experience with large diameters, coupled with a basic scientific discovery of a change in expected gas behaviour at very high pressures, altered his production equation.

> "The effect on the production function of these two changes together, is to shift the equilibrium solution from the minimum thickness with large diameter (i.e. low pressure) to very high pressures (and smaller diameters) for rates less than 200 million feet per day."

Pearl and Enos (1975) applied the same method to similar pipeline technology, considering the effects of improved labour organisation in laying pipes, better pumping control techniques, and improvements in pipe quality and maximum diameter through the invention of spiral welding techniques. They concluded that:

> "On the output side, technological progress has been seen to

> reduce costs (measured in constant prices) at existing rates of output, and to expand the range over which economies of scale can be achieved; on the input side to economise on all factors of production, and to reduce the possibilities of factor substitution",

and that "technological progress has economised on resources, not exploited shifts in their relative prices".

These observational studies emphasise the importance of experience and cumulative introduction of innovations. They are distinctly heterodox, at least by implication; take for example Chenery's statement that:

> "In a sense technological change is involved whenever a new motor is designed, even though no new engineering principles are involved, merely because the outcome is uncertain."

- the last four words contradict the neoclassical assumption of perfect knowledge and hence of "optimisation" ("Clark's neoclassical fairy tale"; Ferguson (1967b)). The idea of scale-augmenting technical change is likewise outside the bounds, and reduction of factor substitution possibilities is a blow to the Cobb-Douglas production formulation which theoretically allows labour-capital substitutions in either direction.

Work reviewed in the preceding section is also entirely consistent with the concept of technology changing with scale; recall particularly Moore's comments on the example of water-pumping equipment supplied by Schuman and Alpert (1960). Later studies fill in the picture considerably. Walley and Robinson (1972) point out that "different limitations will occur at different capacities". The effects of technological limits in process plants are considered by Ball and Pearson (1976). Limits take a number of forms, including resistance to pressure and temperature, and requirements for structural changes or expensive on-site fabrication beyond certain thresholds of physical size.

Changing limits are also associated with changing processes at different scales, e.g. Huettner (1974) on electricity generation equipment:

> "Small plants and large plants frequently utilise different parts of the technological spectrum of an ostensibly common process. For example, the largest steam-power plants operate at higher pressures and temperatures and hence make more use of high-temperature metallurgy."

Dover and Watson (1982) examine the interaction of constraints and process changes in the scale-up of cement manufacturing plant, and Cantley (1979) in Ethylene plants. Buzacott (1980) discusses scale and process choice in the steel industry, as does Stewart (1985) in the cement industry. Hughes (1971) shows how the development of electric power has involved innovations which successfully surmounted 'insuperable' barriers with surprising regularity.

Particularly interesting is the work of Richard Levin (1974), (1978), who has built on a number of the engineering studies to produce a theory of 'scale-augmenting technical change'. He argues (following Pearl and Enos) that changes in factor prices cannot explain the massive increases in plant scale in many process industries (e.g. steel, cement). Starting from the proposition that:

> ".. from an engineering standpoint, 'how to build it bigger' is recurrently seen as a potentially fruitful area for innovative activity"

he proposes a theory of change aimed at overcoming bottlenecks in the production process and shifting to new processes when "insignificance effects" imply little potential for further cost reduction. Levin's case is documented by evidence from process changes in the manufacture of sulphuric acid, ethylene and ammonia. Greenberg, Hill and Newburger (1979) have proposed a more detailed model of process change and applied it to the ammonia production industry. One of the most interesting predictions of such models is that (Levin, 1978):

> "At any moment, the character of an industry's technology plays an important role in determining the rate and direction of future advance. The technology itself

> generates concrete, identifiable problems upon which engineers and applied scientists focus their innovative efforts."

Levin particularly points to the possibilities of exploiting latent economies of scale, improved process yield and reduction of maintenance requirements as recurring technological problems. There are striking parallels with the work of Nathan Rosenberg, whose study of technical change in machine-tools and military and civil engineering (1974) finds that:

> ".. science and technology progress, in some measure, along lines determined either by internal logic, degree of complexity or at least in response to forces independent of economic need ..."

As Blair (1948) and Jewkes (1952) point out, it is not obvious a priori that technological change must lead to increases in scale. The development of electric power, precision tools, automatic control equipment, lightweight materials and alloys, new welding techniques and improved communications could all be argued to give opportunities for reductions in scale. A full explanation would presumably need to encompass "behavioural" influences; for example Gold's (1974) study of scale economies in the Japanese steel industry suggests that increases in blast furnace sizes "were not based on proposals buttressed with persuasive technical analyses", but had more to do with less tangible and less quantifiable managerial goals. Similarly, Ghemawat's (1984) study of capacity expansion in the titanium dioxide industry incorporates the view that:

> ".. focusing on the static determination of prices in homogenous industries is inadequate in explaining many competitive interactions. More fruitful is a combination of industrial organisation and the industry history approach taken at business schools."

These questions, particularly with regard to the evidence as to the causes of large firm size, are examined further in the next section.

David Huettner's (1974) study of economies of scale in electricity generation, cement manufacture and steel-making suggests that incremental and evolutionary technical change has benefited large plants more than small. Hollander (1965) has studied incremental process changes in Du Pont Rayon plants, and Derkx, Kammerman and Rijst (1978) in steel plants. Buzacott and Tsuji (1980) show apparent 'law-like' characteristics of growth of process plant. This is a controversial area; Bela Gold (1981) is sceptical of such ideas arguing that, contrary to their designation as 'learning effects', they in fact:

> ".. represent the effects not of cumulative repetition of past practices, but of changes in: product designs; product-mix; operating technology; management planning and controls; materials quality; and labour capabilities and incentives",

and that the concept means nothing more than "the summation of all improvements regardless of causes". There must be some truth in this, and surveys by Cantley and Sahal (1979) and Dutton and Thomas (1984) show that all of the causes mentioned by Gold do play their part in 'learning' effects. (Changes in operating scale also seem to be relevant to cumulative productivity improvements.)

6.2 Industry Studies

The kinds of engineering and technological considerations discussed above carry over into many of the studies of economies of scale that have been performed over the last twenty years, particularly in regard to the question of the relationship between scale change and technology change. Occasionally engineering concepts are used in surprising contexts: Thomas (1969) documents studies of cost estimates for computers that employ a 'six-tenths rule' type analysis of cost-computing power relationships.

Production function analysis has been employed, quite respectably in terms of economic theory, in the analysis of public service economies of scale. Cowing and Holtmann (1982) provide a survey of cost function studies for the provision of hospital services, mostly drawn from the USA. Martin Knapp has studied UK public services provided by local government- Knapp (1978) (sewage disposal), Knapp (1982) (crematoria). See references therein for similar work in the USA. Watt (1980) has looked for economies of scale in schools, and again provides references to earlier studies.

Studies of economies of scale in transportation equipment have been performed- see Jansson and Shneerson (1978) and Garrod and Miklius (1985) for general cargo ships, and Keith-Lucas (1969), Nicol (1978) and Dathe (1982) for air transportation. Such studies are inevitably complicated by questions as to the appropriate level of analysis. For example, a large supertanker may cost much less per ton of cargo capacity and expend significantly less fuel- but on the other hand it will require much larger, more complex and more expensive port facilities. The same problems apply to the provision of airport facilities for large aircraft. These kinds of 'system effects' apply with great force in the electricity generation industry- see below.

Economies of scale have been examined in publishing, both for newspaper (Rosse, 1967) and journals (Baumol and Braunstein, 1977). In each case substantial economies were found.

Naturally enough, however, it is on manufacturing industry that most researchers concentrate. The studies of Pratten, Scherer and their colleagues have already been mentioned. Within manufacturing industry, Maxcy and Silbertson (1959) made an early study of economies of scale in car manufacture in the UK. More recently, Owen (1983) has done an excellent study of the European car, truck and white goods industry.

This study is worthy of attention for a number of reasons. Firstly, confirmation is found for the view of cumulative technological improvements, appropriable by the individual firm. Secondly, as one might expect, m.e.s. of plant is found to have risen since the Maxcy and Silbertson study. Thirdly, Owen lends considerable credibility to the concept of 'learning' as a 'dynamic scale economy'; in the case of cars, for example:

> "Total company volume emerges as the most useful dimension of scale in this industry, best able to elucidate scale economies, to explain unit cost movements over time, and to explain recent international patterns of costs."

Friedlander, Winston and Wang (1983) find that total firm size is the best measure of potential scale economies in the US car industry.

6.3 Process Industry Scale Economies

It is on the very large scale process industries, such as steel, cement, chemicals and electricity generation, that the greatest attention has fallen, not surprisingly in view of the absolute magnitudes of costs and relative advantages of scale posited, as well as the potential costs of drastic errors. One suspects that the interest in ethylene plants, for example- Woodhouse, Samols and Newman (1974), Cantley (1979), Betts (1982)- has been in part due to the serious overcapacity problems in that sector since the 1974 oil price shock.

A number of studies in the chemical industry have been mentioned. Lau and Tamura's (1972) study of Japanese petrochemicals plants is notable for its application of a production function technique which does not assume homotheticity (constant rates of return to scale at all sizes of plant). This study found strong scale economies to capital and, in common with similar studies of automated process plants, extremely high economies with respect to labour inputs. Materials and energy costs did not alter significantly with scale. Ghemawat (1984) found "learning" effects in cost reductions over time in operating titanium dioxide plants- relatively common in the chemical industry, a reminder that such plants are not simply bought "off the shelf" like food mixers and switched on- they have to be coaxed into performing. Reference to the studies cited above (e.g. Cantley, 1979) will readily show that a chemical plant is an exceedingly complex piece of equipment, with hundreds or even thousands of pumps, furnaces, coolers, distillers, control systems, recycling circuits, etc. Whilst modern computer control systems help considerably. The coordination of all the operations and sub-processes is exceedingly complex and the optimum operating configuration takes time to reach. In this sense, the seemingly archaic arguments about division of labour- and J S Mill's comments on "cooperation" of functions- are still applicable.

Norman's (1979) study of economies of scale in the cement industry compares successive m.e.s. estimates (by Bain, Pratten, Scherer) and finds a rapid increase in the period 1963-1972. As well as making his own estimates, Norman points out the strong location effects in this industry, due to the high weight/value ratio of both product and raw materials. McBride's (1981) study bears out the Levin thesis on scale-augmenting technical change, pointing out that basic cement kiln technology has not changed since 1925 and arguing that kiln sizes have been able to increase drastically, due to improvements in rotation and heat-maintaining techniques. Limited statistical support is demonstrated for change in scale effects over time.

There are dissenting views, however, e.g. Sigurdson (1979) and Spence (1980) argue that cement of an 'acceptable' quality could be economically produced at very much smaller scales than the supposed m.e.s. This would be achieved by re-adoption of an old process (vertical kilns replacing horizontal kilns).

Another process industry, brewing, has been studied in the UK by Cockerill (1971), who also collected a wide range of published material on the steel industry (1974).

The recent work of Bela Gold and colleagues at the Case Western Reserve University has been motivated by a perceived need for "more systematic and deeper analysis of the interactions of technological, economic, and managerial factors," concentrating particularly on the steel industry- Gold (1974), Boylan (1975), Gold, Rosegger and Boylan (1980). They have drawn attention to the influence of managerial objectives and expectations and Gold (1979) has proposed evaluative methods based on concepts of 'factor dominance' and the analysis of the so-called "network of productivity relationships".

6.4 Electricity Generation

By far the greatest number of studies of scale economies have been carried out in the field of electricity generation. A major reason for the abundance is the requirement in the USA for all electric utilities to provide detailed plant-level information, which is published by the Federal Power Commission. This yields a source of microdata of unequalled quality, allowing detailed comparisons between hundreds of plants over long time spans. These studies have been a testing ground for the advance of the general modelling of production technologies, according to Cowing and Smith (1978) who provide a detailed review of 21 econometric studies in the period 1947 to 1978. In parallel with this mainly economics-based research there have been at least as many studies by engineers working in the industry, with little apparent cross-reference to the findings or the methodology of the economists- e.g. Kirchmayer (1955) is a well-known engineering study, seldom considered in the economics literature. On top of these are contributions from outside groups.

I will not review the whole of this literature here. (See James and Tayler (forthcoming) for a more complete survey.) The progress of econometric studies in the electricity supply industry can be traced in the surveys by Galatin (1968), Huettner (1974) and Cowing and Smith (1978). A wide variety of methodologies and assumptions have been used, which in part account for the consistent disagreements that still exist about the nature and level of scale economies. As Huettner and Landon (1978) put it:

> "In a real sense, a researcher studying scale issues is frequently forced to choose which type of specification error he prefers."

As a ruthless simplification it can be asserted that most studies in the 1950s showed the availability of increasing returns in generation, but that later studies tend to imply that these returns decline rapidly for many large plants. The fact that Ling (1964) and Galatin (1968) found increasing returns to scale at all sizes, for example, may reflect the fact that few very large units were included in their samples. Discussions of the development of the fossil fuel technologies and the difficulties and barriers to scale-up of generating technology (Gray 1969; Tombs 1978) tend to give indirect support to this view. A range of studies suggest that scale economies may become exhausted at unit ratings of between 300 MW and 450 MW- see Huettner (1973), Abdulkarim and Lucas (1977) and Fisher (1982). Despite this, units have in fact been constructed two and three times this size.

Generally, though not always, the effects of technological change have been found to be important. Galatin (1968) found that "an important feature of technological change has been the introduction of larger machines", whilst Cowing and Smith's (1978) survey finds that "the evidence also suggests that technical change and ex ante scale effects are interrelated". A recent study by Joskow and Rose (1985) finds different scale/cost curves for different technologies, and documents the fact that very large units are no longer being constructed. The authors attribute this to poor operating reliability of very large units and to the reductions in the rate of demand increase. The scale-reliability relationship is also confirmed by Fisher (1982); the implications for generation expansion policies are examined by Burness, Cummings and Loose (1985).

The Joskow and Rose paper also confirms the existence of capital cost-reduction due to experience effects for both operating utilities and architect/engineers. Kennedy and Allen (1979) give a case-study analysis of such effects, which form an important part of J C Fisher's analysis (1982). Fisher believes that:

> "The replication of a series of identical generating units opens up an entirely new and profoundly different avenue for reducing the capital cost of generating capacity. The economy of scale assumes a new form, and manifests itself as the reduction of cost that can be achieved through the scale of operations in replicating large numbers of identical units."

(A very similar argument has been advanced by Western (1979) for paper mills; he argues that large numbers of a standardised small paper machine would bring capital costs of production below those of the 'world-scale' giant machines which have been built.)

More than with almost any other industry, in public utilities the total system or firm size is of greater significance than the plant size. The need to support large reserve capacity in order to maintain supplies in the face of fluctuating demand and occasional unit failure, the economics of electricity transmission, and the hazards in predicting and meeting future increases in demand (which utilities are generally obliged by law to do), make the evaluation of optimum firm size even more difficult than usual. Again opinions vary, with some significant recent studies placing optimum firm size (based on conventional cost or production function analysis) quite low compared with the largest in existence in the USA - e.g. Christensen and Greene (1975) and Huettner and Landon (1978).

The dynamic effects of generation expansion problems on scale choice are an interesting finding of some research on the economics of electricity generation. Tsuji (1980) reviews the literature on expansion models under uncertainty. A simulation approach has been used by some researchers, e.g. at the Los Alamos Scientific Laboratory (see Ford (1980), Ford and Yabroff (1980), Ford and Youngblood (1982)). The simulation models take account of the fact that larger units tend to have larger planning and construction lead times, thereby incurring greater relative financing costs, and making them more vulnerable to errors in demand estimation. These considerations tend to increase the advantages of generating systems based on small units even where those small units suffer relative cost disadvantages in static comparisons. See also Behrens (1985).

Least 'mainstream' of all (from the economics point of view) is Amory Lovins (1976, 1977, Lovins and Lovins 1982). No doubt some would object to the mere inclusion of a consultant for 'Friends of the Earth' being included in a survey with pretensions to serious analysis. Yet this attitude is mistaken; as Gerhard Rosegger (1980), (a "respectable" industrial economist) says:

> "If the empirical evidence on scale effects in large economic units were reasonably clear-cut, there would be little room for controversy. As it is, however, we have no standard by which to provide unequivocal evaluations;

> besides we are dealing with an issue that transcends purely economic criteria and spills over into the political and social scene."

Lovins' work is not strictly an empirical study of economies of scale in the way that most economists would understand the term, for indeed it insists that the political and social questions are an integral part of the 'problem of scale'. It is also notable for emphasising completely different technological problems, arguing for example that power for heating is very inefficiently supplied by using very high temperatures to produce extremely 'high grade' energy in the form of electricity to be returned to 'low grade' heat of tens of degrees. This polarisation between First and Second Law (of thermodynamics) efficiency is an example of what could reasonably be called a different "paradigm"; for Lovins the technology poses and generates a completely different set of puzzles and questions, and shifts development to a completely different path.

7. FIRM SCALE ECONOMIES

There is now a considerable body of evidence for the existence of technical economies of scale at the plant level. The weight of the evidence indicates that, within the size ranges of plants considered, the cost curves are generally L-shaped. If the U-shaped cost curve is to be rescued, then it will be through the demonstration of diseconomies of scale with respect to management.

It is a commonplace that the general scale of production and organisation at all levels of society has been subject to dramatic increase (Eilon, 1979). This has provoked strong criticisms from some quarters- e.g. Schumacher (1973), Sale (1980), Julien and Lafrance (1983). Growth in the scale of technology is often blamed (Jones, 1981). Yet, as far as firm sizes are concerned, this cannot be the whole story. Prais (1976) points out that, in Britain:

> ".. the hundred largest plants accounted for 11 per cent of manufacturing net output in 1930 and exactly that same proportion in 1968; during that same period ... the share of the hundred largest manufacturing enterprises rose from 23 to just over 40 per cent".

He suggests that this implies that technological factors do not account for the relative increase in firm sizes. Further evidence that plant sizes have maintained a constant relationship to industry size is provided by Simmonds (1969a), (1969b) for various kinds of chemical plants, and by Martino and Conver (1972) and Sahal (1981) for electricity generation. Bain (1956) and Scherer et al (1975) found some statistical links between market size and plant scale. Thus at the plant level there seems to be a case to support Smith's theorem that "the size of the market limits the division of labour". However, the growth in firm sizes implies the influence of other forces.

The study of industry structure is vast, as early studies such as those of Sargant Florence (1948), (1962) have given way to increasingly sophisticated conceptualisations. The effects of economies of scale on structure are still matters for debate rather than accepted relationships; for example Davies (1980) expresses doubts concerning:

> ".. the interpretation of past empirical work apparently showing a strong relation between minimum efficient scale and concentration ... this result may be misleading given the potential problems of identification and measurement errors associated with the statistical proxies often employed to measure minimum efficient scale."

This being the case, what is the evidence for economies of scale for firms- i.e. for multiplant as opposed to single plant operation? And what effect does the scale of management have?

7.1 Multiplant Economies

The major empirical study of multiplant operation, Scherer et al (1975), found "an extraordinarily complex amalgam of technological opportunities, institutional constraints, and behavioural adaptations". If attention is directed solely at the division of labour between plants, the evidence of substantial economies is sparse (Beckenstein (1975) only finds savings of 2-3 per cent). Wahlroos (1981) suggests risk spreading as an explanation of multiple operations, and Teece (1982) analyses further possibilities. Multiplicity of production equipment has not been shown to be a significant productive advantage by itself, however. There are even examples where different companies share the same plant - Vitorovich (1983) discusses the growth of joint ventures in producing important car components such as engine blocks.

Scherer et al attempted, through their interviews in a range of industries, to assess the importance of claimed advantages of size of firms, and in particular they addressed the sources of economies suggested by Robinson (1931). (See Section 3 above.) Very few were found to be of any practical importance in the majority of industries; for example the advantages of large-scale advertising were felt to be very slight, except in brewing and possibly cigarette manufacture. The advantages of larger size for materials procurement was assessed as slight or non-existent in every case. The possibility of product specialisation was found to be of moderate importance in the bearings and refrigerator manufacturing industries, but, as the previously cited work by Beckenstein suggests, even this effect was not important in general.

7.2 Scale in Distribution

Studies of economies of scale in distribution have largely focused on road transportation, and have been generally inconclusive. Smykay

(1958) surveys studies on the US motor carrier industry, and concludes that:

> "Too much has been made of the cost of production side of this problem. The assumption that shippers are purely cost-oriented must be properly investigated as to its validity ... it is too early to present dogmatic solutions to the problem of public policy for this segment of the transport industry."

An early study by Cadbury (1935) in the UK found no economies of scale for large carriers and, in some cases, advantages of small over limited mileages. Kolsen (1956) found no advantages for large firms in Australia, and Roberts (1956) reached a similar conclusion for the USA. Chisolm (1959) found that economies of scale were of minor importance, and that there were some diseconomies, in milk collection in England and Wales (see also Walters (1961) and Chisolm's 'reply').

7.3 Scale of Management

'Management' is popularly associated with bureaucracy when it grows large- witness 'Parkinson's Law' and the 'Peter Principle'. Scherer found that large scale of management, even given the supposed advantages of central specialised staff economies, was as often felt to be a handicap as an asset. Robinson certainly thought this might be so; Bannock (1971) and Blair (1972) almost take it for granted that large scale leads to definite diseconomies in the efficiency of management. Beckmann (1960) constructs a theoretical argument to the contrary. However, as Caplow (1957) points out:

> "There is an almost universal belief that the administrative and overhead components of any organisation increase out of proportion to increases in its size. There are remarkably few studies bearing directly on this point, however."

This sounds a little bit familiar. We are moving on to ground occupied more by organisational behaviourists than by economists, and there is a sizeable literature in that field, which has been surveyed by Keith Dale

(1982). Some research in the management science area is suggestive of difficulties with increased scale; for examples, Stachowicz et al (1982) in coal mining, Smyth (1982) in postal sorting offices, and Stringer (1982a), (1982b) in the control of large engineering construction projects. These, however, deal with qualitative problems without giving any comparable quantifications of the effect on the whole enterprise.

Shorey (1975) and Gill and Warner (1979) demonstrate that industrial conflict, as measured by strike incidence, tends to increase with plant size. Shorey found a slight negative correlation with firm size, which was attributed to better personnel management- the effect here is not clearcut, because the largest firms also tend to have the largest plants. Marginson (1984) found that disputes and strikes were positively correlated to both firm and plant size in a large sample of UK manufacturing concerns. Cason (1978) in a review of literature on organisation size for managers suggests that smaller plants enjoy better industrial relations generally.

McNulty (1956) found a linear relationship between administrative costs and value of plant in the US electric power industry (1949-1953); this implies constant returns to scale on the assumption that management was as efficient at large scale as at small- which really begs the whole question again.

7.4 Scale in Financial Administration

Perhaps the best-quality measures of the size-efficiency relationship is provided by a series of studies of economies of scale in financial institutions, whose "management" is the nearest equivalent to "production equipment", although of course the introduction of new technology may be expected to have a significant effect. These studies encounter some methodological problems- for example, when money is the business's 'fixed capital' and measure of costs, can a money measure of output also be used? Benston (1972) concludes that production functions (rather than cost functions) are the appropriate means, with 'output' measured by numbers of accounts opened or loans made (rather than their monetary value).

This problem has led to some wrangles- e.g. Coates and Updegraff (1973), Murphy (1976). Longbrake and Haslem (1975) note the diversity of methodologies, which they believe accounts in part for the fact that no clear consensus has emerged concerning the existence of economies of scale in financial institutions.

Benston (1972) reviews earlier studies in the specialised banking literature and finds significant economies of scale which he attributes to use of lower-skilled labour, fewer processing and administrative staff, and shifts in technology. He claims that the evidence is as good as in public utilities. (Public utilities still have the best range of empirical studies; however, as we have seen, it does not give an unambiguous verdict). Taylor (1972) finds evidence for economies of scale in large credit unions, based on cost-function analysis. Koot (1977) says that production function analysis is methodologically superior, and uses it to show that there are no economies with scale in credit unions. Wolken and Navratil (1980) claim that Koot's equations were wrongly specified, and recalculate, apparently showing small economies of scale.

Houston and Simon (1970) find economies in life insurance costs. Bell and Murphy (1968) and Murphy (1969) examine division of labour in banking. Murphy fits a Cobb-Douglas function to demonstrate economies of scale in bank trust departments. However Mullineaux (1978), whilst finding economies of scale, casts doubt on the appropriateness of the

Cobb-Douglas - as we might expect from research in other areas. Gough (1979) finds no economies of scale in Building Societies; this was challenged by Barnes and Dodds (1981), but Gough (1981) maintained his position, and said that mergers could only be explained by managerial theories of the firm, and not by efficiency arguments.

This is far from satisfactory, obviously; perhaps methodology is to blame, possibly the wrong questions are being asked. Sutherland (1980a) has an interesting hypothesis. He argues from some of these studies that functional differentiation is responsible for reducing the extent of economies of scale in organisations. For example, the Taylor (1972) study of credit unions focused on size alone, whereas Koot (1977) looked at 'activity variables', which, Sutherland argues, are proxies for organisational complexity, and that is why the latter found decreasing returns to scale. Sutherland develops his argument quite plausibly, presenting evidence that electricity utilities with technological diversity tend to have higher costs. He quotes work by Eslick (1970) showing that the profitability of the top 500 US firms in 1959-61 declined as product diversity increased. See also Starr (1975), Sutherland (1980b).

7.5 Innovation and Scale

There are two other frequently cited sources of economies from overall size. The first of these is 'learning by doing'. Wilson (1975) and Duchatelet (1982) show that the existence of the possibility of gaining information allowing improvements in the production process through increases in 'experience' justify an increased scale of operations even where there are no static economies of scale. The controversy over the sources of efficiency gains has already been alluded to. Some recent examples of the effect in practice will be found in Dept of Prices and

Consumer Protection (1978), Owen (1983) and Ghemawat (1985).

Secondly, there is what Scherer (1975) describes as "an ample if acrimonious literature" on the question of whether small or large size is most favourable for innovation. Scherer (1980) and Sahal (1983) survey this field, which, like the organisation-size debate, is too large to be covered here. The Schumpeter-Galbraith school of thought holds that innovations are produced by large capitalist organisations, but subsequent empirical studies have not entirely supported this claim. Bannock (1971) asserts that:

> "Many inventions right up to the present day continue to be made under exactly the eccentric, romantic conditions on which so much scorn has been poured by the Schumpeterian school".

The problem of measurement is again inextricably tied up with this debate, for how can one unambiguously determine what constitutes "an innovation"? Numbers of patents are sometimes used as a proxy- but some researchers have suggested that small companies patent more of their R and D output, and that in any case some of the most commercially significant innovations are never patented, in order to protect trade secrets. Two recent empirical studies appear to go against the current fashion by finding that 'inventive activity' increases with size (Soete, 1979; Link, 1980). However, closer examination shows that 'inventive activity' is measured by expenditure on R and D. The implied assumption of equivalence between the two simply prejudges the answer before the question is tested. Lunn (1982) and Kaplinsky (1983) urge caution; Lunn says that:

> "It is inappropriate to infer a specific relationship between firm size and innovative output from observations on the relationship between firm size and innovative inputs until more is known about the production of innovation."

It is again possible that the wrong questions are being asked of the data. As Phillips (1971) suggests, the existence of large firms in concentrated industries may be caused by their previous successful innovations, which they were able to prevent competitors from successfully reproducing. It seems that here, as with the management-size question, an open verdict is the only fair answer to the question, given the framework within which it is usually put.

7.6 Size and Profitability

One might argue, pace the 'Survivor Technique', that since firm sizes have grown relative to plant sizes, there must be some extra economies they are tapping. This is certainly possible, but it does not seem particularly likely on the evidence. Studies of the relationship between size and profitability of companies have not supported the existence of benefits of size, despite the possibilities of monopoly or nearly-monopoly control for large firms. For example Whittington (1980) finds that, if anything, the profitability of UK firms in the period 1960-74 declined with size, although this was compensated by greater stability of earnings (possibly due to diversification). Amato and Wilder (1985) find no link at all between profitability and size in US manufacturing. (We should not forget, however, the fact that early studies of plant level economies were marred by the aggregation problem; it is possible that the same consideration applies in this case, or in others mentioned in this section.) Poensgen and Marx (1985) analysed data on 1487 West German manufacturing corporations for the period 1961-75 and found a weak size/rate of return relationship. Their conclusion was that:

> "... it is not size as such that determines whether a firm is profitable or not, but the way it adjusts to size, copes with it and uses the specific opportunities it offers."

It seems that explanations of the growth of firms will have to take account of much more than just 'economies of scale'. It should be remembered that the typical business organisation of today is not merely a scaled-up and more sophisticated version of that of Adam Smith's time. Very simplistically, one may typify nineteenth century business history as the story of single plant 'firms' moving from owner-management to hired management, and of the beginnings of multiplant operation. Improvements in communications and the growing importance of joint-stock companies have been significant influences. Merger waves around the turn of the century consolidated the trends. However, by the middle of the twentieth century companies were tending to diversify much more into industries well away from their initial areas of expertise. Merger has been a very significant source of increases in firm size, and it is not at all clear that 'efficiency' per se has been the only or even the most important motivation.

Newbould's (1970) study of the British merger wave of 1967-8 concluded that financial factors were not important in the minds of senior management, but rather "desires to move towards increased control of the market" and "to achieve a reduction in uncertainty". The importance of behavioural factors is underlined by Amihud and Lev's (1981) finding that manager-controlled, as opposed to owner-controlled, firms were more diversified and engaged in more conglomerate acquisitions (although perhaps more than one conclusion could be drawn from that). Prais (1976) suggests that the massive shift to institutional share ownership in the UK has been a significant factor due to preferential support for well-known large companies. Whatever the exact truth, it seems clear that many factors quite separate from purely economic calculations have played an important part in the growth of large modern companies, and it would be unsafe to conclude that they are big because they are economically superior.

That economic cost optimisation need not be the driving force behind the growth of firms is well illustrated by the case of the brewing industry in the UK. Cockerill (1976) describes the successive merger waves in that industry and shows that a major force was the desire of the brewers to protect themselves from 'outside' predators, whilst economic arguments about improved efficiency and rationalisation to achieve economies of scale were on the whole only used afterwards. The Price Commission subsequently found that:

> "... large brewers have derived no apparent advantage from larger-scale, more concentrated operations. Their costs and prices are higher and their percentage margins lower than those of regional and small brewers ... In other words, the investment of these substantial sums has not improved the position of either consumer or large brewer."
>
> Price Commission (1977)

8. CONCLUSIONS

The orthodox economic framework for considering economies of scale insists on the restriction of constant factor proportions and no changes in technology. This came about because of the constraints imposed by neoclassical equilibrium theory and not because of the demands imposed by reality. Indeed, it has been shown that one of the most frequently-cited sources of scale economies, the '0.6 rule', directly contradicts the fixed factor condition by asserting the possibility of proportionately reducing one factor input (capital) with increased scale. The technological change restriction is equally inapplicable in practice, and has been discarded by almost all empirical researchers into scale economies. The neoclassical account is thus seen to be an artificial abstraction of no practical value either for econometric study or for prescriptive decision-making. The implications for equilibrium theory of the demonstrated artificiality may be far-reaching.

Similarly, the widely-maintained assumption of U-shaped long run cost curves is refuted, at least at the plant level. The concept of the 'optimum' size of plant is not always upheld, as examples have been given where the cost curve is 'scalloped', having more than one minimum point. Moreover, the determination of the optimum size rests on the assumption that cost-minimisation is the goal of the firm. As Walley and Robinson (1972) point out,

> ".. as a means of optimising an investment decision it is completely wrong ... A study of plant capacity should aim not at minimising costs, but at maximising profit or the utilisation of resources such as capital and labour".

The close link between scale changes and technological changes has been highlighted by many empirical studies. No good study of economies of scale in industry would now neglect to take account of differences in process technology. Moreover, many studies explicitly assume vintage effects, i.e. improvements in capability between different generations of plant. The interdependence of the scale and technology factors is summarised by Pratten's (1971) conclusion that:

> "It is often very difficult to distinguish accurately, the part of increases in productivity for new vintages of plant which are attributable to increases in scale and those which are attributable to other causes, partly because technical progress often takes the form of eliminating the obstacles to building larger plants."

In industries which have been studied over several decades there tends to be evidence of large increases in the 'minimum efficient scale' of plants. The importance of 'scale-augmenting technical change' has been explored by a number of studies, and it has been suggested by some that the exploitation of latent economies of scale has been what might be termed a 'paradigm' for engineering improvements and research effort.

Turning to the efforts made to measure economies of scale, it is quite clear that the high levels of aggregation of many earlier studies have rendered them almost totally worthless. Later studies concentrating on the actual production technologies concerned in individual industries have been much more fruitful, and have indeed led to developments in the field of econometrics. The validity of some of the simpler formulations used for measurement of scale and technology effects has been called into doubt. In particular, almost every researcher who has explicitly tested for the possibility that the widely-used Cobb-Douglas production function does not give a good fit have found that other specifications- for example the nonhomothetic translog function- are superior.

Similarly, the frequently invoked "six-tenths rule" gives only a first-order approximation to capital scale economies. The scale exponent is found to fall in a wide range with a median value between 0.6 and 0.7. Careful inquiry into the empirical sources almost always shows that the exponent increases towards 1.0 at the top of the size range considered. Decomposition of cost elements tends to show that, even with such apparently straightforward instances as the construction of cylindrical tanks, simple geometrical surface area/volume arguments do not give a full explanation of cost variations. Thus, whilst there can be little doubt of the cost benefits of scale-up in many practical engineering problems, we should beware of generalisations derived from engineering 'rules of thumb'.

Despite the shortcomings of many empirical studies there can be little doubt that substantial economies of scale are available at the plant level in a wide range of industries. However, the number and complexity of factors involved means that consensus on the actual levels and extent of such economies is not easily achieved. Studies are often based on engineering estimates of what is feasible, which may be conservatively biased towards the status quo, thus ignoring the potential for further improvements in larger plants, or alternatively may optimistically minimise the technological uncertainties inherent in any major scaleup before it has actually been tried.

The electricity generation industry and the financial services industry have both been claimed to be areas where the existence of economies of scale is very well-established. In the latter case it is easy to find studies which directly contradict that claim. Even in the electricity supply case, which accounts for a very large fraction of all published studies of scale effects, wide divergences of opinion exist. These may be partly due to methodological disagreements. Nevertheless, it is quite clear that even in this industry it is relatively easy to find studies to back up any point of view, despite the number of studies carried out (or perhaps because of the numbers of studies carried out).

There is therefore some justification for the view that 'economies of scale' has been used as a rationalisation rather than as a means of analysis. As Schmemner (1976) says:

> "In sum, 'economies of scale' is vague enough to provide easy justification for any number of decisions on plant capacity. Because it is so vague, its usefulness to managers is minimal."

Michael Thompson has suggested that in another sense its usefulness to managers is maximal in that it allows justification of particular views of the world and the making of decisions on other than objectively analytical grounds (personal communication).

At the level of the organisation, studies of 'economies of scale' are again of little practical value on the whole. A wide range of causes of economies or diseconomies of scale of business organisations are variously claimed. Empirical studies tend to be scanty, murky and often contradictory. Methodological disputes and fundamental differences of opinion are not uncommon. There is a widespread belief in the inefficiency of large scale administration, but the evidence in the economics field is as scattered as the evidence for plant-level economies was fifty years ago. Explanations of the causes of large firms will probably have to include behavioural factors.

A comprehensive 'Economic Theory of Scale' is still out of reach. I find Bela Gold's conclusion impeccable (1981):

> ".. effective development of the economic theory of scale- and of other sectors of the economic theories of production and costs- seems to require increasing knowledge about the actual characteristics of the industrial operations about which analytical models are to be developed."

It is only a return to the earlier observational tradition which has allowed any progress in understanding scale effects to occur. It seems clear that a dynamic vision holds out the best hope of providing a full account of the phenomenon of increasing returns, despite the formidable analytical problems that changes in technology and a dynamic rather than a static theory will pose. To these must be added some notions of the behavioural constraints; arguments "as if" cost-minimising optimisation in a world perfectly understood by every manager were true will not explain how industries behave, nor tell us how they ought to behave. In short, we need what Nelson and Winter (1982) call "an evolutionary theory of economic change".

Chapter 3: A Simple Simulation of Dynamic Diseconomies of Scale

In this chapter we will examine the way in which static scale economies are affected by a range of dynamic factors. The usual measures of economies of scale deal with the capital cost of an item of plant or equipment. This view encompasses only a static cost figure, and ignores questions such as whether capacity will be properly utilised over the lifetime of the plant. The possible pitfalls of this approach are pointed out in the case of large petrochemicals plants by Walley and Robson (1972).

This chapter will discuss some "dynamic diseconomies of scale", introduce a simple model designed to explore them, and present illustrative results of some preliminary investigations with the model. It will be shown that even when substantial capital economies of scale exist for constructing production plant it may be more efficient to build "suboptimal"-sized units.

1. INTRODUCTION

Since the model is not industry-specific we will refer to "units" of plant or equipment, which might signify whole factories, or other production systems e.g. electricity generators.

"Static" economies of scale means that relative capital costs decline with increasing size of production units, at least within certain limits. However, other characteristics of the production system change with increasing scale as well. In general, lead times for construction and planning of units increases with size. This factor leads to several effects which may militate against building very large units:

The earnings effect. Small units with short lead times will tie up cash unproductively for shorter periods, costing less to finance, and starting to earn a return sooner than large units.

The forecasting effect. Inevitably, forecasts of future demand are inaccurate, and they are in general less accurate the further forward one is forced to look. Units with shorter lead times will have an advantage because there is a reduced chance of being surprised by changes in the environment. Gross over- or under-capacity are less likely, and so risk is lower.

The control effect. Short lead times also mean that past undercapacity mistakes can be corrected more easily, and a production system based on small units should show less of a tendency towards overcapacity. (For a discussion of these effects, with particular reference to the electricity supply industry, see Ford (1980) amd Ford and Youngblood (1982).)

There is obviously a step effect arising from trying to match a smooth demand curve to a step-function formed by adding units of discrete sizes. Clearly there will not be a perfect fit , but smaller units imply smaller steps and a better approximation.

These effects arise from external causes as well as from the characteristics of the production technology. There is often also a purely internal force at work. The learning effect comes from the fact that costs of constructing identical capital goods tend to decrease as more units are built. This cost reduction is captured in the "learning curve" or "experience curve" (Dutton and Thomas 1984).

2. THE SIMULATION MODEL

In the model, an imaginary industry is faced with the problem of building and operating capacity in order to meet an exogenously specified demand. There is only one decision-maker, only one "company", in this industry. The company is given a single scale of units to operate, and the purpose of the simulation is to compare the results of different choices of unit scale given identical decision rules and demand curves. There are no competitive interactions, and demand is completely inelastic.

This is a simple operational/financial model. In each successive time period our "company" incurs costs for units of capacity under construction, and receives revenue for demand satisfied, less fixed costs for all units in operation. A simple forecasting model is used to predict future demand up to the construction lead time of the size of units being considered. Simple decision rules are used to determine whether extra capacity is ordered or units are retired from service. (See Appendix 3B for the full specification of the model.)

The units have a range of attributes which can be altered independently of the model. Scale and lead time are the most obvious of these attributes. Capital costs, which are spread out evenly over the construction phase, are arranged so as to show static economies of scale. The model employs a 90% learning curve for capital cost reduction with respect to completed units of capacity. That is, for every doubling of the number of units constructed, the cost of each unit falls by a factor of 0.9.

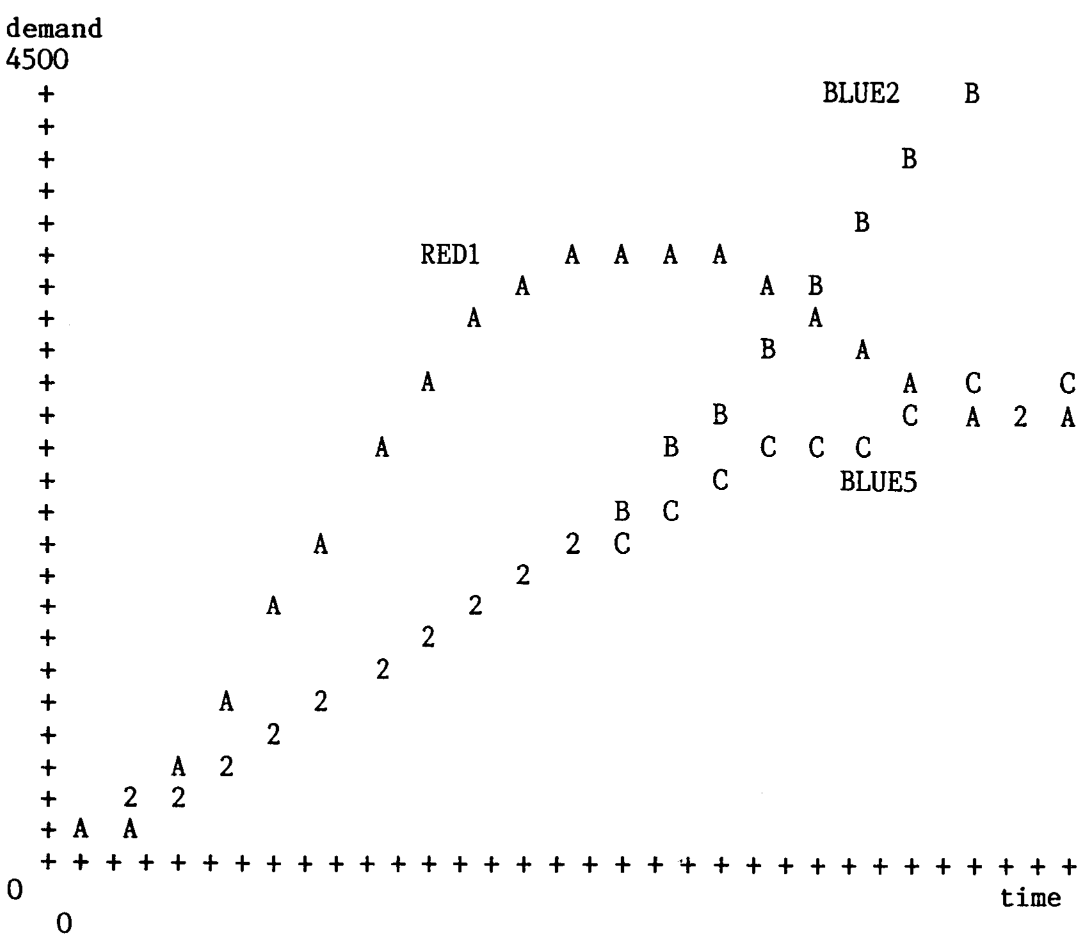
There is another important element in the model, relating to financial performance. It is assumed that the company has a "bank account", which gains interest when in credit and is charged when overdrawn. This is a fairly crude way of taking account of the costs of money. It has been found that in many situations interest charges form a significant fraction of the firm's costs in the simulation run.

The model is implemented in the BASIC programming language to run on a microcomputer. (The program listing is Appendix 3C.)

3. EXPERIMENTS ON CAPACITY-FITTING PERFORMANCE

As already stated, the model was originally conceived with the intention of studying diseconomies of scale. However, rather than attempting to represent the complex characteristics of any particular industry (by introducing "real" demand curves, estimates of scale economies, lead time, reliability, capital intensity, cost of money, and their variations over time) it was felt important to attempt to gain some insight into the working of some of the different effects of scale described in the first section. For this reason we will present some indicative results on financial performance, and then go on to discuss the causes of performance variation by using the model to illustrate the effects of varying lead times, etc.

Fig 3.1: Demand Scenarios



The aim is to see how varying scale and lead time affect capacity fitting (and hence financial performance). Three demand scenarios are used: rapid growth followed by sudden "catastrophe" and decline; steady and then accelerating growth; and steady and then declining growth. These three scenarios are captured by the three demand series RED1, BLUE2 and BLUE5 (Fig 3.1). They are listed in Appendix 3A.

Units of five different sizes were employed, and this standard set of units is described in Table 3.1.

Table 3.1: Unit Specifications

Scale (Output)	Lead Time	Cost per unit of output
100	24	380
200	27	329
400	33	284
900	45	240
1500	54	215

The third column of Table 3.1 shows that there are significant economies of scale over the whole range of unit sizes. Nevertheless Table 3.2, which gives the final "bank balance" for each run in every demand series/scale option, shows that the practical outcome favours small units in the RED1 and BLUE2 scenarios, and gives ambivalent results in the BLUE5 scenario. The ambivalence is due mainly to the relatively low level of demand in BLUE5, which means that the discreteness of the units of supply becomes even more important. The final demand level is about 2800, which is satisfied with little waste by two units of 1500, but with substantial inefficiency by four units of 900. Hence the poor result for the system based on unit sizes of 900. Because the other two scenarios have higher overall demand levels this kind of effect, though still present, is relatively less important.

Table 3.2: Performance of different unit scale in three scenarios

Unit Scale	Final Balance in Scenario RED1	BLUE2	BLUE5
100	-288	-161	-7
200	-248	-80	33
400	-391	28	47
900	-921	-30	-99
1500	-1141	-102	80

(All balances in '000 currency units from model)

Thus whilst a scenario of permanently accelerating growth (BLUE5) confirms the strategy of building the biggest possible units to achieve maximum scale economies, in other environments earnings are maximised with units of scale 400 (modest and declining growth - BLUE2) or 200 (growth followed by collapse - RED1). Exact financial outcomes in any particular case will obviously depend upon the relation between capital and other costs, and other parameters; for ease of comparison the levels of over- and under-capacity are used hereafter.

Clearly the diseconomies of scale represented in Table 3.2 must be due to dynamic effects in the model, the most important being the forecasting and step effects. Table 3.3 shows the cumulative under- and over-capacity for each simulation run, and the total mismatch is plotted in figs 3.2 and 3.3. Total error is shown to increase with increasing unit scale and with increasing unit lead time; the two are covariant (refer to Table 3.1).

Table 3.3: Standard Simulation Runs Capacity Mismatches

Scale	Lead Time	Undercapacity	Overcapacity	Error Sum
RED1 Demand Series				
100	24	38544	8950	47494
200	27	39790	14095	53885
400	33	53109	22615	75724
900	45	78691	51697	130388
1500	54	86299	88704	175003
BLUE2 Demand Series				
100	24	28948	544	29492
200	27	32824	920	33744
400	33	42157	1652	43809
900	45	58140	3636	61776
1500	54	77473	6768	84241
BLUE5 Demand Series				
100	24	4414	3535	7949
200	27	5646	6366	12012
400	33	8194	9515	17709
900	45	14515	19836	34351
1500	54	24300	18521	42821

Fig 3.2: Standard Runs, Absolute cumulative capacity error vs. Scale

```
error
200000
  +
  +
  +         A = RED1                                          A
  +         B = BLUE2
  +         C = BLUE5
  +
  +
  +                               A
  +
  +
  +
  +                                                           B
  +               A
  +                               B
  +     A  A
  +               B                                           C
  +     B  B                      C
  +               C
  +     C  C
  +
  + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + +
0                                                               scale
   0
```

Fig 3.3: Standard Runs, Absolute cumulative capacity error vs. Lead Time

```
error
200000
  +
  +
  +                                                         A
  +     A = RED1
  +     B = BLUE2
  +     C = BLUE5
  +
  +                                         A
  +
  +
  +
  +                                                         B
  +                   A
  +                                         B
  + A     A
  +                   B                                     C
  + B     B                                 C
  +                   C
  + C     C
  +
  + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + +
0                                                           lead time
   24
```

How much are the dynamic diseconomies related to scale, and how much to lead time? A way to tackle this question is to fix all unit lead times (and hence forecasting horizons) to the same distance, and see how errors vary with scale alone. The results of setting all lead times to 24 and 33 (corresponding to the normal lead times for units of scale 100 and 400 respectively) are given in Tables 3.4 and 3.5 respectively, and are plotted in Figs 3.4 and 3.5.

Table 3.4: Fixed Lead Time = 24

Scale	Lead Time	Undercapacity	Overcapacity	Error Sum
RED1 Demand Series				
100	24	38544	8950	47494
200	24	34412	14917	49329
400	24	33668	25574	59242
900	24	34811	65417	100228
1500	24	48450	110855	159305
BLUE2 Demand Series				
100	24	28948	544	29492
200	24	29824	920	30744
400	24	31211	1507	32718
900	24	36177	3273	39450
1500	24	42302	7598	49900
BLUE5 Demand Series				
100	24	4414	3535	7949
200	24	5092	6013	11105
400	24	6532	9853	16385
900	24	11712	11633	23345
1500	24	19065	23786	42851

Fig 3.4: Capacity Errors for Constant Lead Time = 24

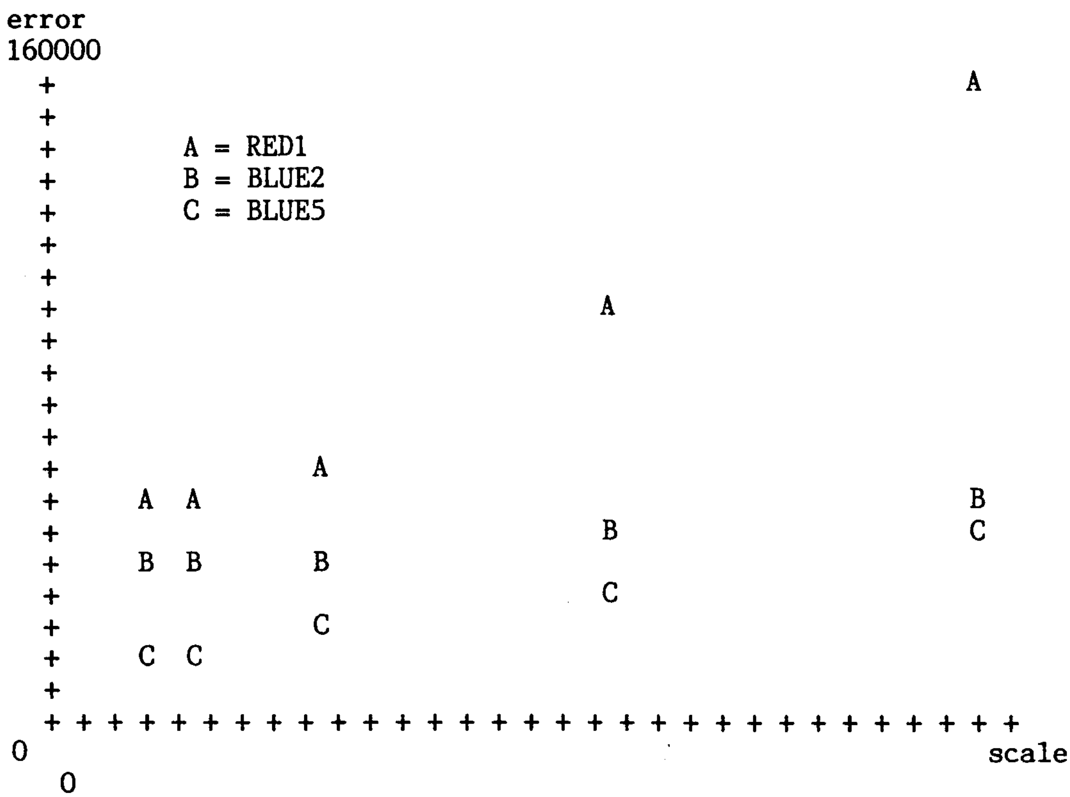
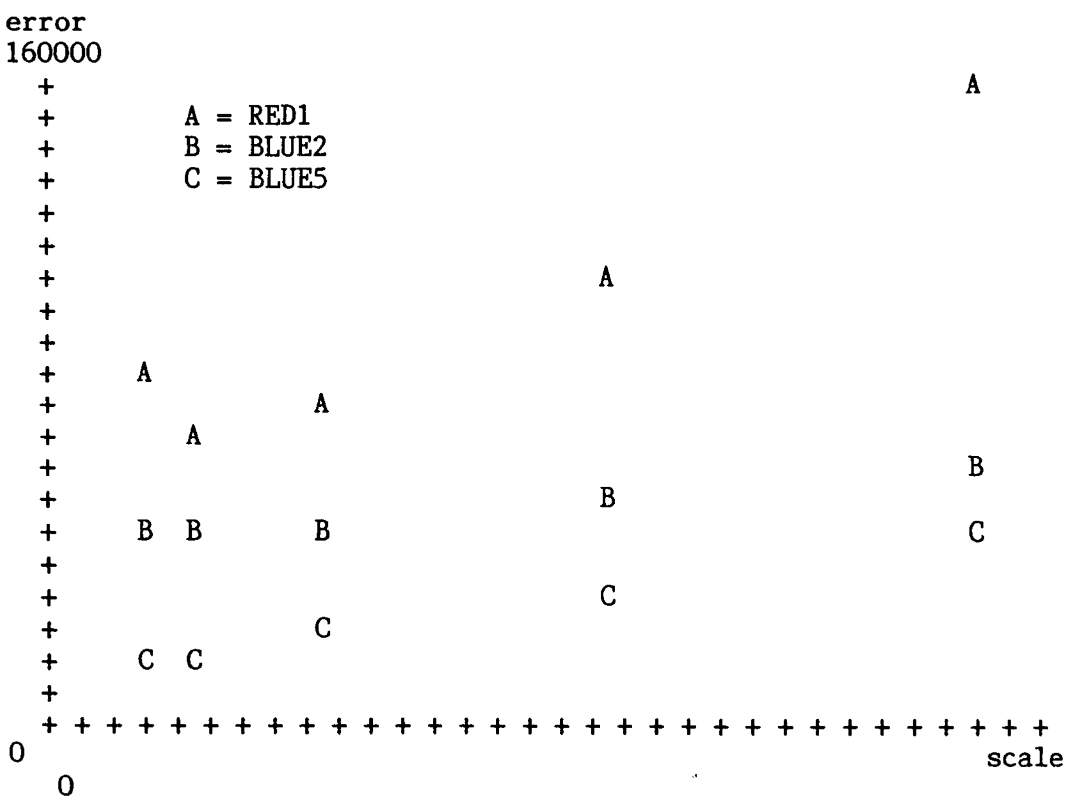


Table 3.5: Fixed Lead Time = 33

Scale	Lead Time	Undercapacity	Overcapacity	Error Sum
RED1 Demand Series				
100	33	55193	26498	81691*
200	33	51369	12074	63443
400	33	53109	22615	75724
900	33	52114	60219	112333
1500	33	53200	105105	158305
BLUE2 Demand Series				
100	33	39371	566	39937
200	33	40048	944	40992
400	33	42157	1652	43809
900	33	45919	3114	49033
1500	33	50567	6863	57430
BLUE5 Demand Series				
100	33	6135	3456	9591
200	33	7098	5019	12117
400	33	8194	9515	17709
900	33	14209	14130	28339
1500	33	18048	24269	42317

* This is correct; due to decision rule for retiring units allowing withdrawl of only one unit at a time.

Fig 3.5: Capacity Errors for Constant Lead Time = 33



Study of the separate under- and over-capacity errors in Table 3.4 and 3.5 reveals a significant pattern. Overcapacity varies considerably more with unit scale than does undercapacity, which in some scenarios appears to be totally independent of unit size. This result is quite explicable when it is realised that overcapacity errors due to poor forecasts can be rectified by simply retiring units, whilst overcapacity errors cannot be erased in a similar fashion. Much of the undercapacity error will be due to forecasting errors, whilst the overcapacity will be due to the "step effect". Examination of the BLUE5, declining growth, scenario confirms this; forecasts will anticipate higher demand than is actually realised, so there should be no undercapacity due to forecast errors. The results show that both undercapacity and overcapacity vary approximately linearly with scale, confirming this hypothesis.

(Lest it be thought that the forecasting errors produced by this simulation are excessive, it may be noted in passsing that Abdulkarim and Lucas (1977) show that the UK C.E.G.B made forecasting errors of five-year forward demand ranging from -11.3% to +28.8% over the period 1947-1970.)

This idea can be taken further by fixing unit scale at 400 and varying the lead time; see Table 3.6 and Fig. 3.6. These show that overcapacity stays constant or even declines with increased lead time (for the reasons just described), but that undercapacity, again largely a product of forecast error, increases rapidly with lead time.

Table 3.6: Varying Lead Times, Scale Fixed

Scale	Lead Time	Undercapacity	Overcapacity	Error Sum
RED1 Demand Series				
400	24	33668	25574	59242
400	33	53109	22615	75724
400	42	66869	20774	87643
400	54	83740	16445	100185
BLUE2 Demand Series				
400	24	31211	1507	32718
400	33	42157	1652	43809
400	42	51357	1652	53009
400	54	62157	1652	63809
BLUE5 Demand Series				
400	24	6532	9853	16385
400	33	8194	9515	17709
400	42	10465	8586	19051
400	54	12071	6191	18262

Fig 3.6 Capacity Errors for Scale = 400, varying lead times

```
error
110000
 +
 +
 +    A = RED1                A
 +    B = BLUE2
 +    C = BLUE5    A
 +
 +        A
 +
 +                            B
 + A
 +                 B
 +        B
 +
 + B
 +
 +
 + C       C        C          C
 +
 +
 +
 + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + +
0                             lead time
  24
```

Of course the above dicussion ignores costs, and units constructed but never used due to inadequate and over-optimistic demand forecasts still have to be paid for. Nevertheless, there are situations- for example an electricity supply system- where overcapacity can be expensive, but undercapacity might be catastrophic.

These results suggest that there are clear disadvantages accruing to production systems based on large and long lead-time units. It is sometimes argued that such disadvantages may be ameliorated or solved completely by improved knowledge of the future. The implication is that it is only the lack of good forecasting techniques which leads to the problems of capacity planning with large scale units.

This point of view can be examined with the model by running the simulation with not merely a better forecast, but with a perfect forecast. Table 3.7 gives the simulation results when the decision rule was given complete knowledge of the future demand rather than just a forecast to work with.

Table 3.7: Standard Runs, Perfect Knowledge

Scale	Lead Time	Undercapacity	Overcapacity	Error Sum	
RED1 Demand Series					
100	24	883	6588	7471	16%
200	27	1391	12696	14087	26%
400	33	2600	20105	22705	30%
900	45	5148	51054	56202	43%
1500	54	22050	19955	42005	24%
BLUE2 Demand Series					
100	24	1736	1032	2768	9%
200	27	3036	2132	5168	15%
400	33	6539	4034	10573	24%
900	45	13785	9681	23466	38%
1500	54	24032	14828	38860	46%
BLUE5 Demand Series					
100	24	1499	1119	2618	33%
200	27	2953	2074	5027	42%
400	33	6445	4566	11011	62%
900	45	11499	10520	22019	64%
1500	54	21795	20516	42311	99%

The last column gives total error as percentage of the total error accruing when forecasting was employed (see Table 3.3).

This experiment shows two interesting things. First of all, it demonstrates that, except in the cases of the smallest units, even perfect knowledge of the future still leaves appreciable errors, which are entirely due to the step effect.

The second and more interesting result comes from comparing the total error given perfect knowledge with that when imperfect knowledge makes it necessary to forecast. This is done in percentage form in the last column of Table 3.7. Now, even though the large units have a longer lead time, and by implication poorer forecasts, it still turns out that the percentage is much smaller for the small units. In other words, improved forecasting leads to a proportionately greater improvement in performance in a system based on small units than in a system based on large ones.

Of course a relative improvement is not an absolute improvement. The largest unit size shows greater absolute improvement given perfect knowledge. However, the remainder of the size range does not show a very great difference in improvement when the need to forecast is abolished.

Table 3.8: Improvements with Perfect Knowledge

Scale	Sum of mismatches between forecast horizons: 0 and 24	0 and 33
RED1 Demand Series		
100	40023	74220
200	35242	49356
400	36537	53019
900	44026	56131
1500	117300	116300
BLUE2 Demand Series		
100	26724	37169
200	25576	35824
400	22145	33236
900	15984	25567
1500	11040	18570
BLUE5 Demand Series		
100	5331	6973
200	6078	7090
400	5374	6698
900	1326	6320
1500	540	6

Table 3.8 shows the absolute differences in performance given perfect knowledge compared with the two sets of runs which assume constant lead time for all unit sizes. These show that, except in the worst possible case (the largest units and the "least predictable" demand curve), there is greater scope for absolute improvements for systems based upon small scale units.

4. CONCLUSIONS

It should be re-emphasised that this model contains drastic simplifying assumptions when considered as a representation of most real-life industries, most notably in the absence of competition and elasticity of demand. Nevertheless, the diseconomies it demonstrates will always be present at the roots of any more complex model of industrial behaviour, and in this sense the model's conclusions about dynamic diseconomies are more generally applicable:

1) The model has illustrated the existence and importance of the step, forecasting and control effects as dynamic diseconomies of scale.

2) Under the assumptions of the model, it has been shown that these effects can lead to advantages for systems based upon small units, even where there are strong economies of scale of the static kind.

3) Leaving costs aside, and concentrating only on errors in fitting supply to demand, it has been shown that overcapacity in a system is a product of unit size, whilst undercapacity tends to be the result of forecasting errors attributable to long lead times.

4) Even where the problems of forecasting are ignored, it has been shown that there will still be significant errors in capacity fitting in model systems based upon large units.

5) Finally, it has been demonstrated that, other things being equal,

there is not much greater scope for performance improvements from superior forecasting techniques in model systems based upon large units than in systems based upon small units.

A full investigation of the model of dynamic diseconomies of scale is not pursued further. A full analysis would demand that the 63 runs performed and described above be expanded upon, with investigation of the effects of using different forecasting parameters. However, the significant result is that the model has already shown circumstances in which, even where there are appreciable economies of scale to be gained by building large production units, this need not be the optimal strategy.

Chapter 4: A Simple Formalisation of Technical Change

It is already clear that we cannot proceed with purely static models. Chapter 2 has shown that issues of technology are closely bound up with issues of scale; thus to study scale change we must also have an understanding of technical change, which is another very important potential source of "increasing returns". In this chapter some ideas about innovation will be developed, which are illustrated in the following chapter.

The conceptualisation and representation of technical change is a difficult problem. The conventional production function formalisation certainly has its uses, but does not allow progression beyond the idea that technical change is exogenous to the economic system. It is also somewhat removed from the realities of the process of production. In Chapter 2 it was seen that, if theory has trouble with realistically portraying scale changes and technical innovation, it has even more difficulty with the many instances when the two effects are compounded.

There are few conceptual tools lying around waiting to be picked up. It is necessary to begin almost from first principles. Here some very basic and simple ideas about the engineering processes underlying technical change, and the conceptual processes of those engaged in innovation, are developed into an analogy. This analogy converges with ideas current in the sociology of technology and recent studies of innovation. However it arrives by an unusual (and original) route.

The simple formalisation developed here leads to some testable hypotheses. Furthermore, it can be used in a much more detailed economic model of the increasing returns arising from economies of scale, technical change, and the interactions between the two.

1. LIMITS AND CONSTRAINTS

What are the determinants of the capabilities of a technology or of a piece of physical equipment? What governs, for example, the maximum speed of a train, the fuel-efficiency of a generator, or the capacity of a chemical plant? And what are the rules (if any) which determine the changes in performance as a technology "evolves"?

The limits to what is technologically possible at a given time can take many forms. At the most fundamental level, we have limits and constraints imposed by simple physical laws; for example, the laws of thermodynamics dictate the impossibility of building a perpetual motion machine. Other examples include the maximum possible chemical reaction rates, energy conversion efficiencies, or evaporation temperatures.

Another set of constraints is imposed by materials and their strength, compressibility, resistance to deformation, tendency to fatigue and fracture, and so on. The raw material inputs or fuels for a process or engine similarly constrain the possible outputs from the process or the power delivered by the engine.

There are other constraints which relate to the technological artefact as a whole; for example, its reliability, tendency to breakdown and maintenance needs. (The lifetimes of the brick linings of cement kilns showed a tendency to seriously deteriorate in the first very large-diameter kilns, a problem which had to be solved by the introduction of new materials.) There are also constraints involved in the construction of artefacts. An example is the current limit on the size of the towers used in certain chemical plants due to the impossibility of transporting them from the workshop to the plant site.

There are also some more nebulous constraints- for example difficulties of control with high outputs or temperatures or speeds, or arising from a multiplicity of units requiring coordination. Limits in such cases are less well-defined and clearly introduce the capabilities of human operators or of computer systems, which are more subjective. (This is an example of the problem of bounded rationality.) Van Wyk (1985) discusses a range of possible limits to technological capability, including those listed above.

Any complex technological artefact is made up of a large number of components, each of which will be subject to a set of these kinds of constraints. Furthermore, the artefact is not merely a random construction of its components; it must be assembled in a particular way, and the parts must be in proportion to one another. The characteristics, limits and potential of any one component will have an effect on some or all of its neighbours, and hence on the performance of the whole. For example, a turbine generator may be capable of delivering 100 MW, but if the boilers supplying steam are too small, or if the cables and transformer to take the generated current are inadequate, then the potential capability of the turbine will never be realised. A balance between components is necessary for 'optimal' performance, and the balance may have to be achieved with respect to several variables at once.

Limits may change with time. New materials or alloys may be discovered with superior performances. New techniques of construction may be developed- for example Pearl and Enos (1975) show how the invention of spiral welding greatly improved oil pipeline technology. The capabilities of electronic control systems may be improved by faster and more powerful electronic hardware or improved software. It even happens that scientific 'laws' are modified- Chenery (1949) shows that a basic scientific discovery relating to gas behaviour at very high pressures changed the possibilities inherent in pipeline transportation.

The arrangement of components may also be changed over time. Rearrangements may be relatively minor, as with the introduction of multiple planetary coolers in place of single rotary coolers in some modern cement plants. There may also be major morphological changes in the technology of the type discussed by Zwicky (1967)- for example a wide range of jet engines have been patented which use different arrangements of parts and operate in different media with different propellants. Another example of a major rearrangement, from the cement industry, would be the change from stationary vertical kilns to horizontal rotating kilns.

So we have the notion of a technology defined in terms of its parts, each subject to a set of constraints. In addition, the whole artefact, and logical sub-assemblies of it, will be subject to constraints set up by their internal relationships- the balancing problem- and by the technically feasible arrangements that are possible between them. All these constraints are liable to change over time as "knowledge", at a number of levels, increases. The possible performance and cost of the artefact can be expressed in terms of the components and of the relationships between them.

2. A MATHEMATICAL ANALOGY

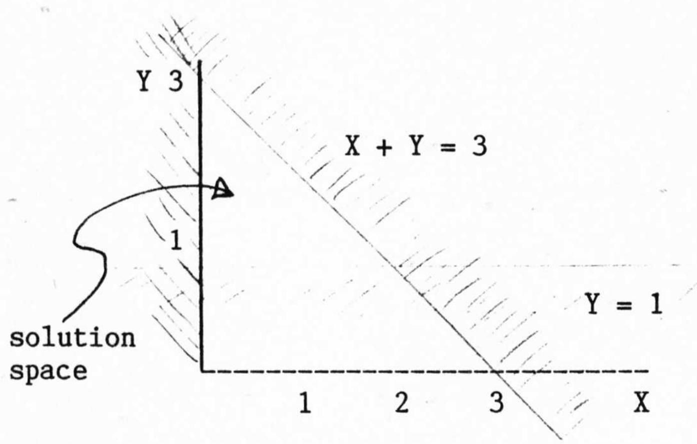
This description suggests the analogy of a mathematical progamming model. A mathematical program consists of a number of variables, which are subject to a set of constraints, and which have to be optimised with respect to some function known as the objective. A lot of effort has been expended on solving mathematical programs, and a fair amount is known about certain classes of problem.

The first and most important characteristics of mathematical programs is that they are in general very difficult or impossible to solve exactly. Even small and simple problems can take a long time to optimise without the use of computers. In the special case of linear programs, exact solution is possible in general. A linear program has the property that each constraint equation and the objective function are formed by adding or subtracting multiples of the problem variables to a constant term. We can define a solution space to a program by attributing a dimension to each variable in the problem and then drawing boundaries on a graph corresponding to the constraints. For example, consider the simple two-variable problem:

$$\text{maximise} \quad 2X + Y$$

$$\text{subject to} \quad \begin{aligned} X \quad &> 0 \\ Y &> 1 \\ X + Y &< 3 \end{aligned}$$

The solution can be found graphically by drawing the "solution space" of feasible solutions to the above problem, and inspecting it for the optimum value of 2X + Y:



The solution space is defined by the unshaded area. The maximum value of 2X + Y can be found by drawing successive lines 2X + Y = (constant) for increasing values of (constant). The line representing the largest value of (constant) with at least one point within the solution space corresponds to the optimal solution.

For a linear program, no matter how large, it is possible to find the optimal solution by a method which is analogous to constructing an n-dimensional space (where n is the number of variables defined by the problem) and exploring the boundaries of the solution space for the optimal solution- even when n is as large as 100 or 1000 or more.

However, if the problem is non-linear, then this method breaks down. In fact, no method exists which guarantees a solution to a general non-linear problem, unless literally infinite computing power is available. Difficulties are posed by the introduction to the problem of:

a) non-linearities in constraint equations caused by terms involving multiplying two or more variables together, e.g. $X * Y$ or terms involving powers of a variable, e.g. X^2 or $Y^{1/3}$.

b) similar non-linearities in the objective function.

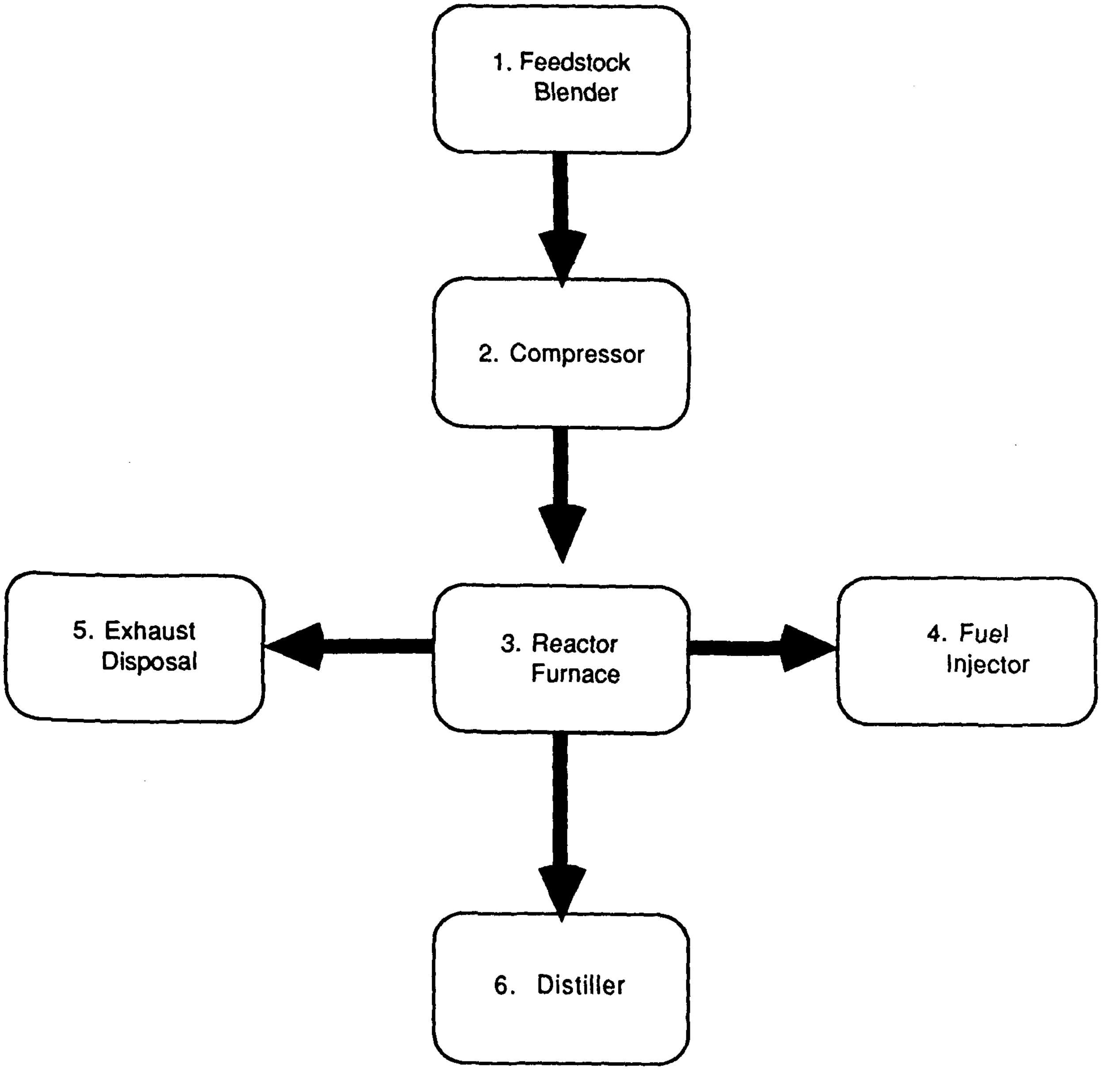
c) the existence of non-continuous variables, e.g. variables which take only integer values.

There seems to me a strong intuitive link to be made between the notion of technological limits and the idea of constraints in a mathematical program. This generates the idea of a technological 'solution space' corresponding to the mathematical solution space, the idea of 'feasibility' being associated naturally with both concepts. The objective of a technological artefact is to maximise its performance (subject to some cost constraint) or to minimise its cost or other input needs (subject to some performance requirement).

To make this more concrete, consider a highly simplified chemical process plant with six main subunits (see Figure 2.1).

The major component of the 'plant' is a reaction furnace (3), which is

Figure 2.1: A Stylised Chemical Production Process



fed with feedstock which must be blended (1) and then compressed (2). Fuel must be injected (4) to support the reaction, and the exhaust gases must be removed and purified (5). The final product must be cooled in the distiller (6).

We can visualise many interdependencies within even so simple a system. The total output can never exceed the capacity of the blender, compressor, furnace or distiller. To maintain the required reaction heat needs a large enough fuel supply, but if the output of exhausts becomes too great the filter will not be able to cope. Output from the furnace may depend on temperature, pressure, and the correct blend of inputs, whilst the dimensions and thickness of furnace walls will affect cubic capacity, heat resistance, pressure resistance, and so on. Each subunit will have separate requirements for labour, power, automatic control, and cost.

Thus the output of such a plant would be a fairly complicated function of a number of the other variables governing the dimensions, capacity, etc, of the subunits. Each subunit would have a cost for any given size, capacity, etc, specification which would be itself a fairly complex function of that specification. Some units would show economies of scale- for example the furnace, if idealised as simply a hollow cylindrical container, would be subject to the "two-thirds power law". On the other hand, some units would show diseconomies of scale, the compressor being a case in point. Finding a minimum cost configuration for a given output will therefore be a non-trivial task, particularly if there is a range of possible reaction temperatures and pressures and possible variations in feedstock mix.

Of course, it is not suggested that it would actually be possible to perform this kind of analysis in detail for any complex piece of technology; hundreds or thousands of variables would be required, and a similar number of constraint equations. Estimation of the coefficients and terms in the equations and objective would be a very risky business too. However the parallels between a very large (high-dimensional) and complex mathematical program may yield some interesting insights for the study of technological change, through consideration of qualitative properties of the progam.

It is clear that a technological artefact is a solution to a highly non-linear program. Non-linearities of types a) and b) above (variables multiplied together, and raised to powers and fractional powers) will be the rule rather than the exception, for two reasons.

The first is that the artefact's holistic properties are more important than the sum of the properties of the individual components, and changes in one sub-unit will have implications for others. Thus effects will tend to be multiplicative rather than additive, and there will probably be a number of multiplicative "interaction" terms in both objective and constraints. Secondly, many relationships and properties of the technology will depend upon allometric relationships. (See e.g. the discussion of the use of power laws in estimating costs of various items of production equipment in Chapter 2, section 5.) Such relationships automatically lead to the introduction of power exponents on variables (e.g. $X^{0.6}$ for the 'six-tenths rule').

Non-linearities of type c) may also be present- a description of the cement plant with planetary coolers would need a variable stating the number of coolers used, which could only be integer-valued. The result is a hypothetical mathematical program with a very large number of variables and a pathological state of non-linearity. How can it be solved?

The theory of mathematical programs says that there is no real hope of solving it. No hope, that is, if by 'solving' we mean 'finding the optimum feasible arrangement'. What we must do is to find a heuristic; that is to say, a method of finding successively better approximations to the optimum, although we will probably have no way of knowing how close we are to the optimum or whether we have reached it. We thus commit ourselves to a search procedure within the solution space. (We hope to stay within the solution space- otherwise we find that our latest artefact doesn't work.)

3. SEARCHING AND LEARNING

This idea of heuristic or search behaviour for technological improvement is not new in economic theory (see for example Nelson and Winter (1982) Chapter 11 and references therein). It does represent a clear break from the Neoclassical formulation which assumes perfect knowledge. We have to search because we cannot instantly identify a global optimum. Any combination of technological 'variables' which has not been tried before is in some sense an experiment, and its outcome is to a greater or lesser degree uncertain. As Chenery (1949) puts it:

> "In a sense technological change is involved whenever a new motor is designed, even though no new engineering principles are involved, merely because the outcome is uncertain."

The search model thus carries the implication of "learning by doing", in that knowledge is advanced by the carrying out of a cumulative series of experiments. It also implies that another assumption of Neoclassical economics must be abandoned, namely that all actors have full and equal access to all existing technical possibilities. Nelson (1980) argues eloquently that this cannot be the case under "learning by doing", since different actors perform different "experiments". One may also argue that technical knowledge gained in this way is to some extent non-communicable even between actors who cooperate, since in practice much of the 'knowledge' is implicit rather than explicit, and is contained in management or engineering 'routines'- regular but not necessarily conscious patterns of behaviour. A similar point is made by Cantley and Sahal (1979) in answer to the rhetorical question "Who learns What?".

The Neoclassical formulation works on the principle that technological progress exploits shifts in input factor prices. The mathematical program analogy has more to say about technical change (see below), but can subsume this account. For the costs of the inputs will either appear in the objective function or in one or more constraint equations. The former case will mean that a change in input prices will alter the 'gradient' that the search pattern will seek out within the solution space, while the latter implies that a change in prices will alter the shape and extent of the solution space itself. In both cases the 'optimal' solution may (or may not) be altered, and the search pattern may or may not change course within the solution space.

Attempts by Roberts (1983) and Venezia (1985) to set out formal explanations of the origins of the traditional learning curve employ similar arguments to those above. Roberts explains efficiency improvements in machinery in terms of rearrangements of standard parts under the assumptions that:

a) each part has a multiplicative effect on the overall performance of the whole, and

b) the search procedure is such that there is a 'filter' to eliminate those parts of the solution space yielding a value of the objective lower than a certain fraction of the current best achieved, i.e. there is some way of telling that some possibilities are stupid and preventing purely 'random' experiments from being performed.

A simple computer simulation has been constructed to illustrate this learning process in a succession of stylised 'process plants' with six main subunits based upon the earlier example (Figure 2.1 above). The 'temperature', 'pressure' and 'reaction rate' of the process were determined by various characteristics of the six units. The precise equations governing performance are known only to the computer, and the operator must construct a series of plants with the aim of reducing capital costs. The performance of each plant is reported in detail by the simulation, and the operator must work towards improved performance and lower cost on the basis of these successive reports. The results have been encouraging in the sense that even with such a simple 'plant' of only six components learning-curve-type regularities did appear. The model is described more fully in Chapter 5, and its operation is discussed there. The program listing is provided in Appendix 5A.

It should be noted that my model and that of Roberts assumes that there are no changes in the overall constraints, either in the structure of the constraint equations or in the values of the coefficients. The turning of an invention (new scientific knowledge) into an innovation (new technological artefact and the know-how to use it) will often alter the analagous mathematical program in the way that changes in factor prices do. For example, the substitution of a new material for an old one may change constraint coefficients relating to strength, temperature, resistance, conductivity, cost or other considerations.

More fundamental innovations may change the structure of the constraint equations and the variables which appear in them, e.g. the introduction of centrifugal compressors in the manufacture of ammonia (see Greenberg et al (1979)). 'Basic' innovations would tend to alter the form of the objective function as well- for example a process innovation may be introduced for that very reason, a capital-intensive process with substantial economies of scale often being preferred to a process dominated by materials costs. See Levin (1979) for discussion, and an example from the manufacture of sulphuric acid.

4. TECHNOLOGICAL HEURISTICS

Thus far, the analogy has been drawn between a technological artefact and the solution to a very large, many-variable and non-linear mathematical program. There is the added complication that we have to solve it in the knowledge that the problem may be changing over time, partly through the alterations we are making, and partly through external fluctuations beyond our control (as in 'demand-pull' theories of technical change). A precisely-determined mathematical problem of this kind, with exactly specified structure and known coefficients, has a general degree of difficulty of complete solution that can be regarded as impossible. The analogous technological situation, where knowledge of structure and values is less perfect and where both may be changing over time, can only be more difficult and less tractable. The answer in the mathematical case is to develop a heuristic search procedure, and it has been suggested that a search model of innovation is the appropriate technological counterpart. One of the most interesting questions is to see what the analogy will suggest about the nature of possible and profitable heuristics for the improvement of technological capabilities.

In devising a heuristic we are faced with the problem that it is hard to know in advance what general method for obtaining successively better solutions will be the best. There will be many possible heuristics available at any given time. Equally, at any point in a sequence of search 'trials', there will be many plausible next tries. Here is yet another layer of uncertainty- what is to be done?

A simple argument by Heiner (1983) gives a partial answer to this question. He shows that it is rational for an individual faced with choosing between uncertain courses of action to deliberately restrict his or her choices to a small subset, and that in fact:

> "an agent's overall performance may actually be improved by restricting flexibility to use information or to choose particular actions".

Not only is bounded rationality inevitable- it may actually be useful. (Simon (1978a, 1978b) seems to come close to this idea in the context of procedures for solving complex mathematical problems, which he uses as a metaphor to link research in artificial intelligence with economics.)

Heiner's argument runs as follows. Consider an agent with a particular possible set of actions, and consider the situation when allowing the flexibility to choose an extra action might improve the agent's performance:

At certain times (depending on exogenous factors $\underline{e}$) the new action will be advantageous and at other times it will not. Let the probabilities of the right and wrong times to select the action be $x(\underline{e})$ and $1 - x(\underline{e})$ respectively.

In an uncertain world the agent will not necessarily select the new action at the right time. Let the conditional probability of choosing the action at the right time be $r(U)$, where the uncertainty $U = u(p,\underline{e})$ depends on exogenous factors $\underline{e}$ and the agent's perceptual abilities p. Let the gain in performance from choosing the action at the right time be $G(\underline{e})$.

Similarly, let the conditional probability of choosing the action at the wrong time be $w(U)$ and the resulting loss be $L(\underline{e})$.

Then the expected gain from allowing flexibility to choose the extra action is

$$x(\underline{e}).\ G(\underline{e}).\ r(U)$$

and the expected loss is

$$(1 - x(\underline{e})).\ L(\underline{e}).\ w(U)$$

Thus gains outweigh losses (on adopting the extra action) if

$$x(\underline{e}).\ G(\underline{e}).\ r(U) > (1 - x(\underline{e})).\ L(\underline{e}).\ w(U)$$

or if

$$\frac{r(U)}{w(U)} > \frac{L(\underline{e})}{G(\underline{e})} \cdot \frac{1 - x(\underline{e})}{x(\underline{e})}$$

which is the Reliability Condition.

Greater uncertainty reduces r and increases w, making violations of the Reliability Condition more likely. Thus in situations of greater uncertainty it is less likely to be rational to select the extra action, and more likely to be rational to choose the more restricted set of actions.

In the context of the search for technological improvements we can interpret the exogenous factors $\underline{e}$ as a combination of the structure of the 'mathematical program' (i.e. the constraints imposed upon the technology, and the objective it must seek) and the current state of the technology (i.e. the position within the 'solution space'). Greater uncertainty corresponds to a more complex technological problem; most technological problems can be considered to be highly uncertain, as we have seen above.

Heiner has a strong claim to make from his analysis, namely that greater uncertainty:

> "will further constrain behaviour to simpler, less sophisticated patterns which are easier for an observer to recognise and predict. Therefore, greater uncertainty will cause rule-governed behaviour to exhibit increasingly predictable regularities, so that uncertainty becomes the basic source of predictable behaviour."

Common sense might suggest that more complex and uncertain situations would lead, on the contrary, to less regular and less predictable behaviour. Heiner has shown, in a stylised mathematical world, that it is actually preferable to deliberately exclude certain possibilities. In the language of the mathematical program, that means that it is better to concentrate on a small set of heuristics, to follow a search pattern which deliberately excludes a wide range of possible paths, and to concentrate attention on only relatively few variables at a time.

The heuristics idea is applicable at more than one level. In the most general sense it implies that the same aspects of problems will tend to be tackled first, and that particular ways of solving recurring technological problems tend to be employed. At a more specific level, when faced with the problem of improving successive generations of a particular artefact, it suggests that it will be more profitable to try to change relatively few features of a design at a time. Perhaps the overall form will be kept recognisable similar, and marginal changes are tried in some components. Sustained progress in solving a complex technological problem is only possible when sufficient variables are kept constant for comparisons with previous efforts to be made. Only then is learning possible.

It is my contention that a number of writers on technology and innovation have recently pointed to examples of just this type of regular behaviour in the realm of technological artefacts:

At the 'micro' level, we have what Sahal (1981) calls "the principle of technological guideposts". This states that the basic or fundamental form of an artefact is only rarely subject to substantial change. Improvement is sought by means of incremental change rather than through total revision. Sahal presents evidence to suggest that the 'essential features' of the farm tractor have been fixed for 40 years; that the design of rock drills was essentially determined in 1897; that the inland steamboat reached its ultimate form in 1840 and was unchanged for the rest of its days; that modern passenger aircraft are still in many respects following the design conventions of the early 1930s; and that the modern electric motor owes its genesis to the design of 1910.

The importance of incremental innovation has been recognised by many people, but Sahal has pointed to the apparent preservation of form. (Waddington and Thom have used a similar concept of developmental 'chreods' to map the development of biological form- see Thom (1983).) In the language of the mathematical program, search effort is concentrated on changing parameters but not structures of equations. Removing or adding a single expression in an equation may drastically reshape the solution space, whereas small changes to coefficients will usually only deform it slightly. In the language of technology, we can either redesign every artefact from scratch, so that every new development is a prototype, or we can take certain design principles for granted, and concentrate research effort on improving certain selected aspects of performance. Heiner's argument articulates which course is generally preferable, and why.

Sahal points to the persistence of form in the development of technologies. Others have suggested that the actual nature of the search for improvements follow regular patterns; that is, the particular kinds of behaviour innovators engage in have common elements. Rosenberg (1969) cites developments in the machine tool industry and in military and civil engineering, and finds that:

> "An important common denominator running through these examples is the persistence with which firms attack what, at any given time, they regard as the most restrictive constraint on their operations. This suggests that it may be possible to formulate a microeconomic approach to

technical change in terms of a bottleneck analysis."

Rosenberg's observation is entirely consistent with the mathematical program analogy. If we accept that the innovation process involves the devising of means to overcome present constraints, then this is equivalent to finding a way of relaxing the constraint equation which most strongly bounds the solution space. Rosenberg is suggesting that this strategy is being consistently followed in preference to others that might be possible, e.g. looking for totally new processes or attacking several constraints at once. Of course it may not always be known for sure what the most important constraints are. Heiner's argument says, however, that in an uncertain situation it is reasonable and desirable to exclude some possibilities, so what is important is that there is some consistency in approach to the technological (or mathematical) problems. This consistency may be 'arbitrary' in the sense that we cannot be objectively certain of its correctness, and indeed it may be determined by any number of 'extraneous' factors. This analogy, therefore, does not exclude the possible influence of sociological factors on the innovation process.

Rosenberg goes further than just pointing out that a certain search strategy is frequently employed. He suggests that this leads to the result that

> "Science and technology progress, in some measure, along lines determined either by internal logic, degree of complexity or at least in response to forces independent of economic need ... this sequence in turn imposes significant constraints or presents unique opportunities which materially shape the directon and the timing of the inventive process." (Rosenberg 1974)

This theme has been taken up more recently by Dosi (1984) with his concept of a "technological paradigm", which he defines as:

> "a 'model' and a 'pattern' of solution of selected technological problems, based on selected principles derived

> from natural sciences and on selected material technologies." (p 14)
>
> " ... a technological paradigm (or research programme) embodies strong prescriptions on the directions of technical change to pursue and those to neglect ... Technological paradigms have a powerful exclusion effect: the efforts and the technological imagination of engineers and of the organisations which they are in are focused in rather precise directions while they are 'blind' with respect to other technological possibilities." (p 15)

At an even wider level of generality, Perez (1983) has employed the concept of a 'technological style' which consists of:

> "a kind of 'ideal type' of production organisation or best technological 'common sense' which develops as a response to what are perceived as the stable dynamics of the relative structure for a given period of capitalist development ... more and more branches of the economy will tend to apply the prevailing technological style understood as the most rational and efficient way of taking advantage of the general cost structure."

She suggests that the widespread use of microelectronics will represent such a 'technological style' just as the use of steam power did in the Industrial Revolution. Interestingly, Perez is of the opinion that organisation for factory mass-production and economies of scale was the dominant identifiable style of the last fifty years or so.

5. SCALE INCREASES AS INNOVATIONS

Can the ideas about constraints and heuristic searches be applied to the process of scale change? To answer this question, we must have a more concrete idea of what some of the regular search patterns, 'paradigms' or 'styles' are like. One researcher with specific ideas is Richard Levin who discusses technical change in the chemical industry (1978). Levin believes, like Rosenberg, Dosi and Perez, that:

> "At any moment, the character of an industry's technology plays an important role in determining the rate and direction of future advance. The technology itself generates concrete, identifiable problems upon which engineers and applied scientists focus their innovative efforts."

Levin suggests that recurrent areas of effort in the chemical industry centre on the three goals of improving reaction rates, decreasing maintenance needs, and exploiting latent economies of scale. He discusses three routes to increasing scale. Firstly, the case where there are significant economies to be had from increasing the size of a major element in the process plant- for example reaction furnace which accounts for a large portion of the capital costs of the plant. Allometric considerations would imply that, if certain barriers or constraints can be overcome (e.g. strength of materials, heat loss problems), then substantial savings can be made. The second case is where there are 'bottlenecks' in the production process, and innovative effort naturally concentrates upon their eradication. (See also Ball and Pearson (1976).) The third case is due to which Levin calls 'insignificance effects', where the elements of capital cost in total cost are so low that any scale economies in plant are insignificant when compared with the total. The only way of overcoming this problem is by switching to a completely new process with greater capital intensity.

As an example of the first kind of innovation Levin cites the introduction of centrifugal compressors in the manufacture of Ammonia which allowed substantial scaleup in the mid-1960s. (Greenberg et al (1979) support this analysis.) McBride (1981) suggests that much innovative activity in the cement industry since 1925 has been aimed at removing obstacles to increasing rotary kiln size.

The second kind of innovative activity, the removing of bottlenecks, is exemplified by Levin from the manufacture of Ethylene, where steam turbine and compressor sizes, use of multiple furnaces (i.e. constraint on maximum furnace size) and site fabrication problems have all conspired to limit plant sizes in the past.

The third innovation type, aimed at removing 'insignificance effects', is represented by a change of basic process in the manufacture of sulphuric acid to a technique employing cheaper raw materials and possessing greater economies of scale (whilst being more capital-intensive).

There is in fact a good measure of agreement that considerable innovative effort is directed towards the problem of "how to build it bigger" in many industries besides chemicals manufacture. Hughes (1971) describes how electric power engineers have consistently overcome barriers to scaleup of generator sizes in order to reap further economies of scale. Gold (1974) shows how Japanese steel companies introduced successive innovations in methods of raising top pressure and blast temperatures, adding oxygen enrichment to the process, and fuel injection, in order to increase their blast furnace outputs.

Ball and Pearson (1976) provide a conceptual description of scaleup in terms of overcoming technological barriers and constraints. More than most other scholars, they develop the idea of the importance of allometric relationships between the different parts of a plant or production process. That is, a change in scale always results in some non-linear changes in production relationships, e.g. a change in scale of a particular chemical reaction may make it exothermic (it gives off heat) instead of endothermic (requiring heat to continue).

Finally, it is very often the case that an innovation which raises the possible scale of operations also has an effect upon the minimum scale of operation. This was the case in the example of centrifugal compressors quoted by Levin above- they were simply not economic at small scales. Whilst vertical cement kilns are not feasible for large outputs, neither are rotary kilns economically useful at a small scale.

Joskow and Rose (1985) show that sub-critical and super-critical steam turbine technologies for electricity generation have different efficicent scales; the latter are best over 600MW, but are decidedly inferior at 300MW. Thus innovation may raise minimum scale as well as maximum scale.

6. IMPLICATIONS

There are a number of consequences of looking at technical change in the way outlined here. In the past there has been a sharp discrepancy between the economist's conception of technological progress, depending upon the construction of a number of statistically determined production functions, and the technologist's analysis of innovation at the engineering level (Amendola 1983). There are several problems with the 'moving production function' view of technical change, and with the debate between the so-called 'demand pull' and 'technology push' explanations of innovation.

It is not my intention to discuss these problems here. (For an overview see Elster (1983); detailed criticisms will be found in e.g. Nelson (1980), Sahal (1981) ch 2, Dosi (1984) ch 2.) It is my contention however that this stylised model is capable of incorporating the competing views of technical change, explaining at the same time how technological evolution is affected by the environment (changes in coefficients in the objective), and at the same time following a dynamic of its own. It is sufficiently rich to be able to encompass an explanation of the 'learning curve' phenomenon, and more general ideas of cumulative technological progress. At the same time, it lends itself quite naturally to the description of technological 'guideposts' for design and 'paradigms' of innovation search. Its disadvantage is that it is too detailed and complex to be of much use in quantitative measurement of technical change in most concrete cases.

However, supposing that we were able to make a simplified analysis of a family of technological artefacts in this way, what would we expect to see in succeeding generations? The first thing is that we would anticipate that the basic structural relationships between the major parts of the artefact would remain the same. Minor process innovations would result in alterations in parameters, but the main equations (constraint and objective) describing the technology would remain the same. For example a steam boiler might have a set of well-defined relationships between its size, length of tubing, operating temperatures and pressures, etc. A minor innovation might improve the heat-carrying capacity of the boiler tubes; the same general set of equations would still govern the relations between the parts, with small changes reflecting the extra heat capacity. An increase in operating temperature or boiler capacity would have a very similar effect on performance as before.

Secondly, a major innovation would produce a significant change in the formal description. So much so, that such a change could be used as a definition of major technological innovation. An example might be the switch to super-critical steam technology boilers (in which temperatures of over 100 degrees Centigrade are employed), or to a different fuel source (oil or nuclear instead of coal). In these cases the equations relating given temperatures to operating steam pressures, or the scale-output relationship, could be drastically changed.

(Recall also the research of Chenery (1949) into pipeline transportation technology discussed in Chapter 2, section 6 and in section 1 of this Chapter above; a scientific discovery about gas behaviour at high pressure, coupled with improvements in stress resistance in materials, led to a dramatic shift from large diameter-low pressure systems to small diameter-high pressure designs.)

Thirdly, we would expect to see residual incremental change and improvement over time i.e. "learning effects". Any artefact which is not an exact copy is, in at least a limited sense, a technological experiment. Moreover, experience in operating a technology will lead to suggestions as to how it may be improved, generating better 'experiments' when the next unit is planned. These improvements will not always be explicable in terms of specific innovations (although they may be linked to them). The technologist will observe and realise that certain constraints are not important to a particular artefact and can be locally ignored. For instance, it may be seen that a boiler never operates anywhere near its temperature and pressure safety limits; the next such to be constructed can safely have thinner walls. This is not innovation, in the sense of a new idea; it is experience leading to a saving and a mapping out of the technological solution space.

Fourthly, due to the fact that knowledge acquired through experience is not always directly appropriable, there will be asymmetries in technological capability between different 'owners' of technological knowledge e.g. different firms will have different input-output relations for their plant. (This is of course implicit in most, if not all, conceptions of cumulative progress.) Different boilermakers will not have carried out quite the same sequence of experiments; as a result they may favour slightly different arrangements of components, the use of different grades of materials and different machining processes, even if they do not possess patentable advantages over one another. These will lead to subtly different areas of the solution space being occupied by different actors.

The heuristic attack on the technological problem means that:

> "the course of technological improvement, at least in the form of process innovation, is not nearly so arbitrary and unpredictable as economists of an earlier generation believed."
>
> (Levin, 1978)

One of the great problems of general equilibrium formulations in economic theory is the treatment of technological change. My view is that what is needed is a dynamic and evolutionary economic theory. I find it difficult to see how economic statics could provide the tools for such a theory; on the other hand, how can one formulate endogenous technical change using production functions without specifying all possibilities in advance? This simplified model may provide a more realistic metaphor for endogenous technical improvement.

7. CONCLUSIONS

The most important element in the analogy I have drawn is the heuristic, which has been deduced as a logical necessity arising from the intractable complexity of the problem (mathematical or technological). The idea of an exclusion principle in dealing with complex problems is not new; indeed I suspect that Herbert Simon's "bounded rationality" was first formulated by a route similar to that used here. The idea that there are consistent "boundednesses", which may take alternative forms, has been less widespread, and Heiner's recent contribution seems to go at least one step beyond Simon. Moreover, the approach employed here demonstrates that the different "technological paradigms" can arise solely through the nature of the technology itself. (It is of course likely that many other exogenous factors will influence the choice of paradigm and affect its subsequent development.)

The work of Levin and others suggests that one frequently employed technological heuristic is the pursuit of scale increases. The existence of cultural biases for and against large scale has been discussed by Michael Thompson (1985) (and see Chapter 6 following). We can speculate that the cultural bias affects the choice of technological heuristic and encourages its progress. The combination of these two and their interplay opens up the possibility of a cultural theory of innovation. For example, Utterback and Abernathy (1975) have proposed a model of process and product innovation linked to the life cycle of a technology which is linked with organisational form and managerial attitudes and imperatives. It is clear from their description that they envisage different technological heuristics applying at different stages of the life cycle, for example focussing on maximising functional performance at the beginning of the life cycle, and on minimising production cost via productivity gains and realisation of economies of scale in the mature phase of the cycle.

Finally: the idea that there are certain invariants in the evolution of technological forms is not original, as I have shown by reference to the work of Sahal, Dosi, and others. Their (multiply independent) discoveries have been produced by a combination of empirical observation and an extension of the ideas of Thomas Kuhn, historian and philosopher of science, who first defined the notion of the "Scientific Paradigm". In this chapter the necessity of a technological heuristic is deduced from the nature and complexity of the problem facing the engineer or technologist, and not from any social processes. That is not to say that these may not be relevant; the argument advanced here should be seen as complementary to those of Dosi et al. The heuristic (paradigm, guidepost) is the product of social processes, technological complexity, and perceptual and cognitive boundedness. It is interesting that its existence can be predicted from an essentially mathematical argument, as well as by the other routes.

In the next chapter these arguments are made more concrete and briefly illustrated by the use of a simple simulation model. The idea of innovation as a search process wil be used again in presenting a much more complex model of scale change, technology choice and competition in Chapter 7 onwards.

Chapter 5: Technological Learning Simulation

1. INTRODUCTION

The concept of technological progress presented in Chapter 4 is that of an uncertain search procedure within an area bounded by current feasible technical limits. The adoption of a basic technological configuration allows experimentation within that form, as the constraints are tested and new sections of the possible solution space are explored. Some elements of a technology may be combined in new ways, but the need to adopt technological heuristics means that the search process is always constrained.

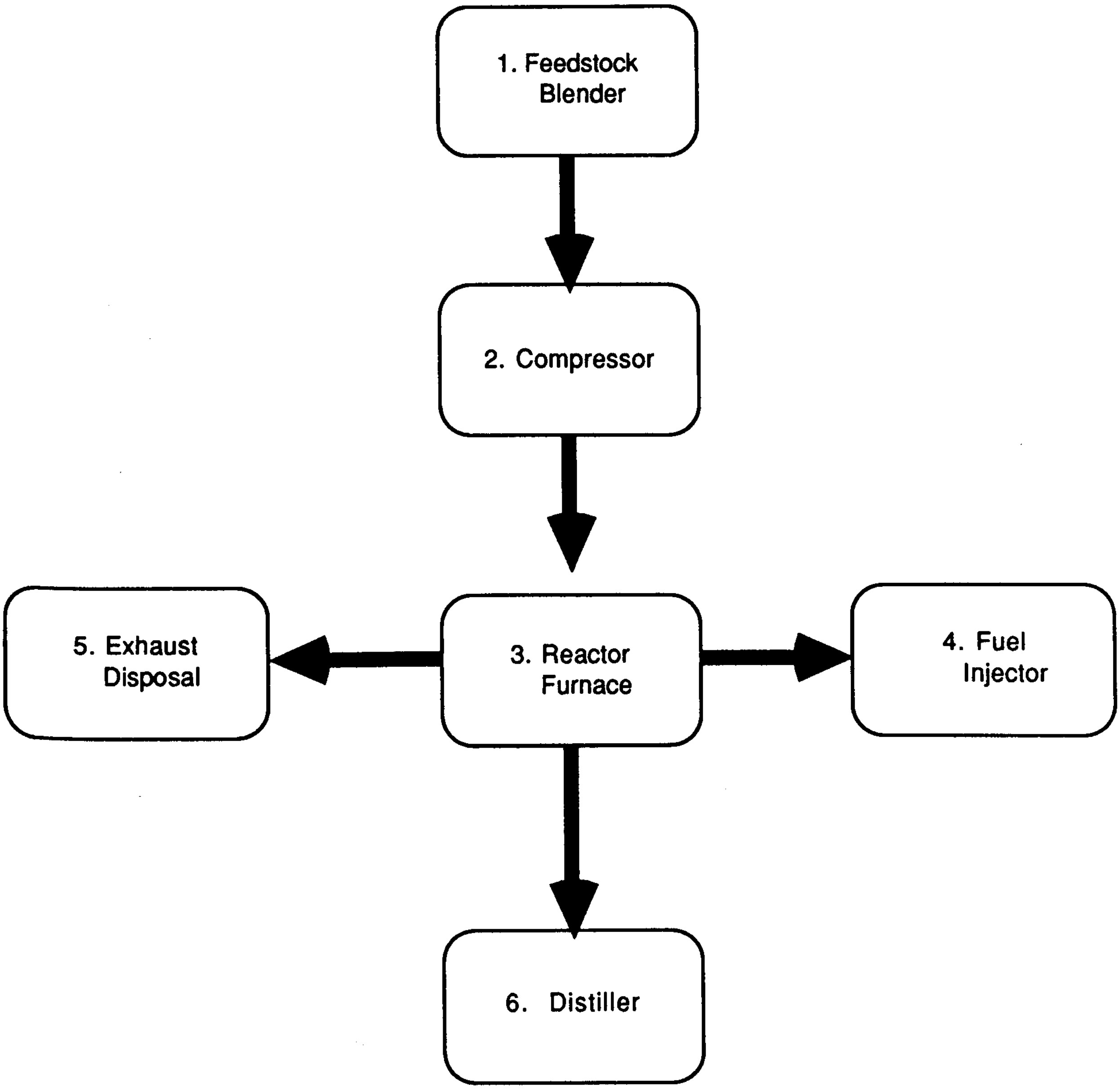
It is difficult to demonstrate this process briefly by producing real-life examples. Here a short-cut illustration is developed by invoking a simple computer model of the evolution of a fictitious technology relating to the manufacture of some basic chemical product. The technology is arranged so as to exhibit the non-linearities discussed in Chapter 4. The specific details of the technical relationships are generated by the computer for each set of innovation "experiments", presenting the operator with the task of exploring the technological "space" to develop superior production plants.

2. THE MODEL

The model is as described in Chapter 4, section 3. There are six main subunits in the imaginary production process: the feedstock blender, the compressor, reaction furnace, distillation unit, fuel injector, and exhaust system (Fig 2.1).

The full mathematical specification of the technology is given at the end of this Chapter. (The corresponding computer program is in Appendix 5A.) It is arranged as follows. The major element of the production process is the reaction furnace. The "constructor" must specify the

Figure 2.1: A Stylised Chemical Production Process



volume of the furnace, and the thickness of its walls (its cost is a function of the two, with scale economies). These together determine capacity, temperature and pressure resistance of the furnace.

The sub-units which feed in an out of the furnace are then specified in terms of their maximum capacities. The constructor must also specify the compressor pressure, fuel injector flowrate (which determines maximum operating temperature), distiller and exhaust capacities (complicated by the fact that multiple units may be employed), the efficiency of the blender unit, and the type of process control system which is to be employed.

All of these elements jointly determine the maximum operating temperature, pressure and throughput of our imaginary production system, constrained by the parameters selected for the components. The relationships between the elements of the process are in many cases non-linear, fulfilling the conditions described in Chapter 4 section 3. (See model specification at the end of this Chapter.) Reaction temperature, pressure, flowrate and blend are combined with the type of process control system selected to determine the output of the production unit:

$$\text{Output} = K * \text{Flow} * (\text{Temp}/1000) * (1-0.5/\text{Pressure}) * \text{Blend} * \text{Control}$$

There are many interdependcies within the system. The total output may never exceed the capacity of the compressor, furnace or distiller. Maintaining the required reaction heat needs a sufficient fuel supply, but if the output of exhausts becomes too great the filter cannot cope. Output from the furnace depends upon temperature, pressure and the correct blend of inputs, and the dimensions of the furnace walls affect cubic capacity, heat resistance and pressure resistance. Each subunit has requirements for power.

Costs are attached to each component, both capital charges and running costs. Each subunit has a cost for a given size, capacity, etc. Some units (e.g. the furnace) show economies of scale; some (e.g. the compressor) exhibit diseconomies. Finding a minimum cost configuration for a given output is therefore a non-trivial task, particularly since there is a range of feasible reaction temperatures and pressures, and possible variations in feedstock mix.

The results of successive innovations are output by the program in the following table:

Control type auto				Plant no. 5		
Total output 923				Yield 92.3%		
Operating Temp 935				Operating pressure 8.80		
	Vol	Thickness	Flow%	Pressure%	Temp%	Cost
Furnace	1000	5.20	100.0	99.4	86.9	1324270
Blender	Coeff. 0.95		100.0			133739
Injector	Rate 18000				100.0	232541
Distllrs 3	Length	180	96.9		96.9	113830
Exhaust	Capacity	100	77.3			64733
Comp. 8.80	Flow	1000	100.0	100.0		36848
Control unit						125000

Electricity cost		264079		Capital cost		2030970
Cap. cost/Unit		2201		Av. LR Cost		683

The top section of the table shows what control system has been selected, the operating temperature and pressure, and the process yield and total output. The bottom section details capital costs per unit of output, and average cost per unit (which includes interest charges and depreciation on the capital costs, feedstock, and power). The middle section reports on the sub-unit characteristics i.e. their sizes, pressure rating and costs. The columns headed "Flow%", "Pressure%" and "Temp%" show to what extent the relevant component is being utilised with respect to its flowrate, pressure and temperature resistances. Thus in the above example the furnace is operating at 86.9% of its maximum permitted temperature, but at 99.4% of its possible pressure and 100% of its flowrate constraints. The exhaust system is coping with 77.3% of its maximum possible output.

3. THE SIMULATION PROCESS

The operator receives a series of prompts from the computer asking for the specifications for a new "plant". The operator is aware of the general structure of the technology, but at the beginning of each run the basic parameters of the model are reset by using random variables. Thus the general kinds of input-output relationships are known, but they cannot be calculated exactly in advance. Given the complexity of the basic equations (considerable non-linearities) and the number of unknown variables, the operator is faced with a significant degree of uncertainty. This can only be reduced by a series of "experiments" as the different components of the plant are optimised to one another.

This can best be explained by referring to a short series of plants from one particular run, which follow on from the table given above (representing the fifth such "plant" in a series of 23):

Control type auto				Plant no. 6		
Total output	937			Yield 93.7%		
Operating Temp	935			Operating pressure 9.64		
	Vol	Thickness	Flow%	Pressure%	Temp%	Cost
Furnace	1000	5.80	100.0	100.0	81.9	1353970
Blender	Coeff. 0.96		100.0			150342
Injector	Rate	18000			100.0	232541
Distllrs 3	Length	175	99.7		99.7	111287
Exhaust	Capacity	85	73.8			57630
Comp. 9.80	Flow	1000	100.0	98.4		39554
Control unit						125000

Electricity cost		289353		Capital cost		2070320
Cap. cost/Unit		2209		Av. LR Cost		670

Plant no. 6 represents a small incremental change from no. 5. The blender coefficient has been raised from 0.95 to 0.96, and the reaction pressure raised by increasing the compressor rating from 8.8 to 9.8 and increasing the thickness of the furnace walls from 5.2 to 5.8. Redundant exhaust and distillation capacity has been marginally reduced compared with plant 5. The result is a slight capital cost saving on these elements, and a rise in the process yield from 92.3% to 93.7%; the plant output rises from 923 to 937. Total capital cost per unit of product is slightly higher (because of the more expensive furnace), but overall costs decline from 683 to 670 per unit output, mainly because of the improved efficiency, and thus better use of feedstock.

Control type auto				Plant no. 7		
Total output 950				Yield 95.0%		
Operating Temp 935				Operating pressure 10.17		
	Vol	Thickness	Flow%	Pressure%	Temp%	Cost
Furnace	1000	6.20	100.0	100.0	78.9	1373760
Blender	Coeff.	0.97	100.0			178012
Injector	Rate	18000			100.0	232541
Distllrs 3	Length	150	75.6		75.5	131432
Exhaust	Capacity	75	67.0			52894
Comp. 10.40	Flow	1000	100.0	97.8		41184
Control unit						125000

Electricity cost		305152		Capital cost		2134820
Cap. cost/Unit		2248		Av. LR Cost		657

Plant 7 repeats the experiment by again increasing blending efficiency and reaction pressure. Exhaust capacity can be reduced again as the yield has improved. The number of distillation units is increased by one as an experiment. There is again a slight improvement in yield to 95%, with a consequent gain in output and decrease in overall costs. Capital costs are still rising, however, and the proportion of capital costs taken up by the furnace is falling. This is the only element of the plant which has significant economies of scale.

Thus economic arguments suggest that to maintain cost reductions it is necessary to increase the furnace size. Plant no. 8 represents a potential doubling of capacity by increasing the furnace volume to 2000. Furnace thickness is increased slightly to relax the pressure constraint; the distillation and exhaust capacity are increased less than proportionately with the increase in scale to improve their utilisation. The result is that capital costs per unit of output fall by about one quarter; overall average costs are reduced from 657 to 611.

Control type auto			Plant no. 8			
Total output 1901			Yield 95.0%			
Operating Temp 935			Operating pressure 10.30			
	Vol	Thickness	Flow%	Pressure%	Temp%	Cost
Furnace	2000	6.30	100.0	100.0	78.2	2148220
Blender	Coeff. 0.97		100.0			244910
Injector	Rate	36000			100.0	462445
Distllrs 3	Length	275	82.4		82.4	216186
Exhaust	Capacity	120	82.7			74204
Comp. 10.40	Flow	2000	100.0	99.1		78948
Control unit						125000

Electricity cost		617796		Capital cost		3349910
Cap. cost/Unit		1762		Av. LR Cost		611

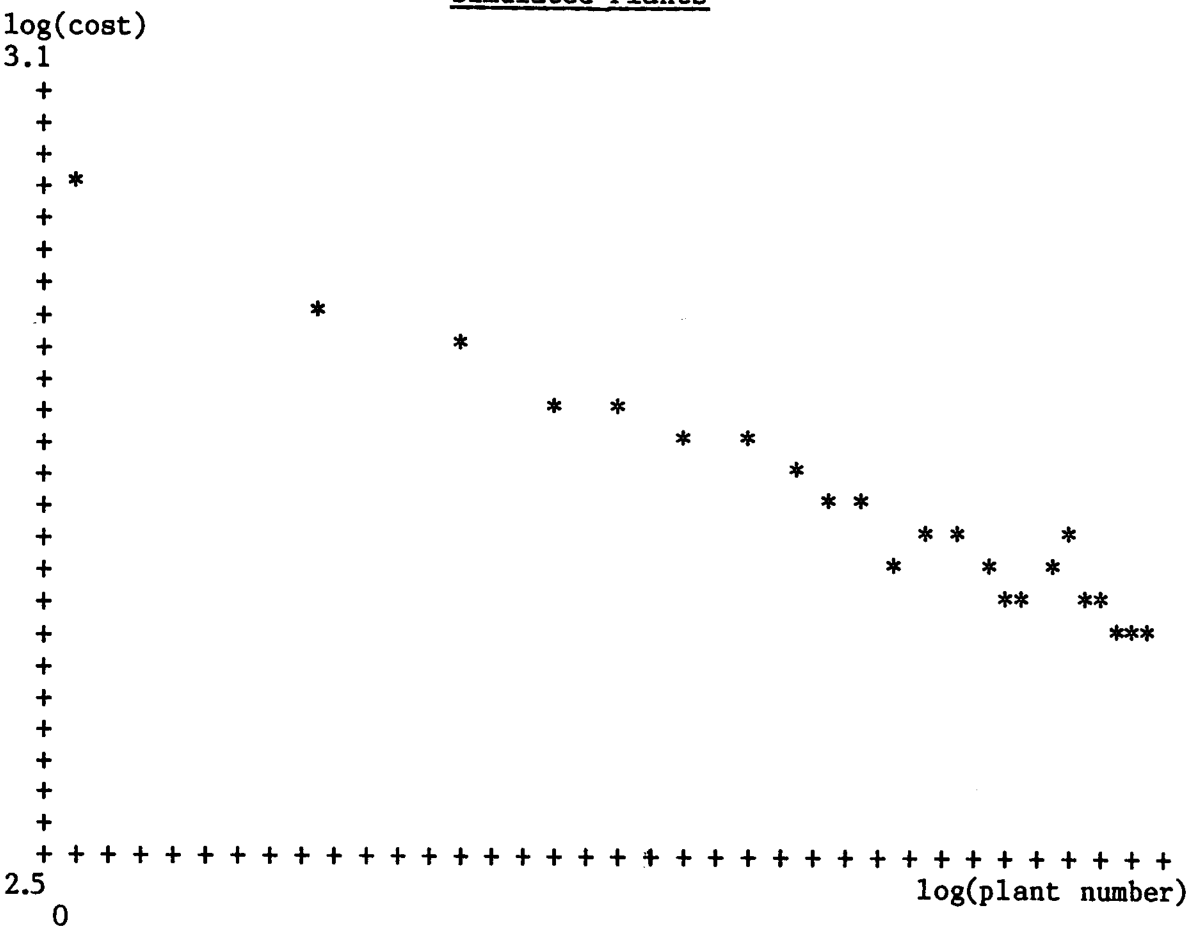
The series of plants continued in this run (results not shown further). Plants 9 and 10 raised the process yield to 97% by improving the blender coefficient, and the furnace wall thickness was further increased to maximise reaction pressure. Plant 11 saw another big scaleup, by a factor of three this time. The following two plants saw an attempt to experiment with changing the reaction temperatures; this was not successful and costs rose slightly before another path for improvements was tried.

This short sequence of fictitious plants should make clear that, even with such a simple model, the innovator is faced with a fair degree of uncertainty about the exact outcome of design decisions; the interactions between the components cannot all be foreseen. The major alternatives are to make small, incremental adjustments to try to match sub-units more effectively; to try to improve the yield of the process by e.g. raising pressure or temperature; or to make major "leaps" by e.g. substantial increases in scale. The risk with the latter in particular is that an efficient balancing of the process at a smaller scale may be disturbed by the allometric nature of the process and production equations.

4. RESULTS

The simulation has been tried several times with the operator set the task of reducing average costs of production over time. The plot below shows this process in operation for the complete sequence described

Figure 4.1: Logarithmic Plot of Production Costs from Successive Simulated Plants



above; log of overall costs is plotted on the vertical axis, and the log of the plant number on the horizontal.

This looks like a very good "learning curve" relationship, and indeed regression of log(cost) against log(plant number) plus a constant gives an excellent fit, with an R^2 of 0.975. In the spirit of the discussion on scale increase and innovation in Chapter 4, it can be asked what proportion of this "learning" is in fact due to increases in scale.

Table 4.1: Results for a Simulated Series of Plants

Plant Number	Total Output	Capital cost per unit output	Average Cost per unit output
1	762	2568	1071
2	862	2344	814
3	889	2256	763
4	910	2226	705
5	923	2201	683
6	937	2209	670
7	950	2248	657
8	1901	1762	611
9	1921	1763	587
10	1941	1819	567
11	5823	1290	514
12	5569	1316	552
13	5742	1268	547
14	11484	1054	525
15	11645	1102	495
16	11645	1073	492
17	11696	1084	508
18	11737	1090	528
19	11617	1071	480
20	11576	1063	469
21	23092	912	460
22	23149	919	455
23	23195	950	453

A simple regression again gives an interesting answer, when we compare capital costs with output and plant number:

$$\text{Log(Capital Cost)} = 4.14 - 0.257 * \text{Log(Output)} - 0.049 * \text{Log(Plant No.)}$$

Capital Cost here is per unit output. This equation shows strong economies of scale (as is largely determined by the model specification). The Plant No. variable is significant at the 1% level, and suggests "learning curve" cost reductions as above. R^2 for this regression is over 0.995.

This particular run is fairly typical; two other runs using different sets of randomised technological parameters produced equally good cost-plant no. regressions, with R^2 of 0.994 (28 plants) and 0.973 (23 plants). In one of these, the slope of the learning curve was significantly different from that of the other two.

5. DISCUSSION

This simulation does not constitue a rigorous mathematical proof. It depends upon the input of a human innovator for its technological changes. Yet that is also one of the sources of its importance; for so does the real-life innovation process. This model stands as a metaphor for that process; it has three important qualitative products:

Firstly, it demonstrates emergent behaviour of the kind predicted. The model is constructed from a consideration of the arguments about constraints and balancing of processes, and the search through a set of "solutions" to the technological problem of (e.g.) minimising production costs emerges as a result. The operator does seem to be obliged to devise simple heuristics for the search process, for example moving the solution in the direction of increasing reaction pressure, scaling-up and then sorting out distillation and exhaust unit efficicent utilisations, etc. The heuristics are not clearly demonstrable in a repeatable way, for they are to some extent subjective - just as in real life.

Secondly, a most significant emergent pattern is the extraordinarily good "learning curve" of average costs from successive plants. Roberts (1983) derives the common mathematical expression of the "learning curve" using two assumptions:

1) Improvements to each individual element of the production process will have a multiplicative effect upon the performance (output) of the unit;

2) The search for improvements in the arrangement of the elements is carried out with the aid of a "filter" so that possibilities which are very much worse than the present system are automatically rejected (although marginally inferior choices are permissible). Thus the search procedure is not completely random; we might say that a very simple "heuristic" is at work again.

This process plant construction model seems to fulfil the criteria set up by Roberts very well. Nevertheless the accuracy with which the results fit the standard learning formulation is striking. Such very high correlations are surprising. There has been considerable puzzlement in the past over why learning effects should fit the usual mathematical formulation (or any mathematical expression, for that matter). A simulation is not conclusive proof by any means, but I believe that these results indicate that the Roberts argument is on the right track. This simulation has provided an illustration of the search process, in which the operator "filters" out poor options.

Third and lastly, the interrelationship between cost reduction through technical improvements and through exploitation of scale economies has been illustrated. In Chapter 2 the difficulty of separating the two effects in practice was alluded to (see Ch 2 section 6.1); there and in Chapter 4 (section 5) the issue of scale increase as an important form of innovation was developed. The model illustrates this process. It has yielded statistical relations between scale, capital productivity and learning over successive technological combinations, showing how both scale and innovation contribute to cost reductions in the simulated technology.

The model developed in this chapter depends upon human, subjective input for its operation. In the next Chapter some interesting issues relating to subjectivity and bounded rationality are discussed.

Annexe: Model specification

FURNACE

$$\text{Cost} = K_1 + K_2 * \text{Flow}^{2/3} * \text{Thickness} + K_3 * \text{Thickness} + K_4 * \text{Flow}^{2/3}$$

$$\text{Temperature Resistance} = K_5 + K_6 * \text{Thickness}$$

$$\text{Pressure Resistance} = K_7 + K_8 * \text{Thickness}$$

$$\text{Yield} = K_9 * \text{Control} * \text{Blend} * (\text{Temp} / 1000) * (1 - 0.5 / \text{Pressure})$$

$$\text{Output} = \text{Flow} * \text{Yield}$$

The temperature and pressure resistance of the furnace is dependent upon the thickness of its walls. Its cost depends upon the thickness and upon the surface area of the furnace, which is proportional to the 2/3 power of its volume (and hence flowrate). The yield increases with temperature and pressure (and also blend and control coefficients); the improvements through increasing pressure diminish.

COMPRESSOR

$$\text{Cost} = C_1 + C_2 * \text{Pressure}^{3/2} + C_3 * \text{Flow} + C_4 * \text{Pressure} * \text{Flow}$$

$$\text{Electricity Consumption} = C_5 + C_6 * \text{Flow} * \text{Pressure}^2$$

Cost and power consumption increase more than proportionately with increasing pressure, implying that very high pressures become uneconomic. This seems a reasonable assumption.

BLENDER

$$\text{Cost} = D_1 + D_2 * \text{Flow} + D_3 / (1 - \text{Blend})$$

This equation implies that moderate improvements in blend efficiency are relatively inexpensive, but that approaching a blend coefficient of 1.0 becomes increasingly costly.

CONTROL

Cost = 5000 Manual

= 45000 Auto

= 125000 Computer

Value of Control = 0.95, 1.00, 1.05 respectively

INJECTOR

$$\text{Cost} = F_1 + F_2 * \text{Rate}^{1.1}$$

$$\text{Temperature} = 1000 * (1 - F_3 * \text{Flow} / \text{Rate})$$

These relationships suggest moderately more than linearly increasing costs with increasing reaction temperature.

DISTILLATION

$\text{Cost} = N * (G_1 + G_2 * \text{Length})$, where there are N distillers of length Length each

$$\text{Capacity} = G_3 + N * G_4 * \text{Length} - \text{Temp} * \text{Flow} / N^{1/2}$$

There is a fixed cost for each distiller, plus an amount proportional to its length. Its heat capacity depends upon the total size of the set of distillers, but increasing their numbers has a less than proportionate effect upon overall heat exchange efficiency.

EXHAUST

Cost = $H_1 + H_2$ * Flow

Capacity = Flow * (1 - Yield)

These are simple linear functions.

AVERAGE COST (for the whole production process) is given by

0.1 * (Capital Cost) + L_1 * (Electricity Use) + L_2 * Flow * (1 - Yield)

K_i, C_i, D_i, F_i, G_i, H_i, L_i are constants generated by the program at the beginning of each simulated series.

Chapter 6: Plural Rationalities - A New Approach to Ideas of Scale

> "If the empirical evidence on scale effects in large economic units were reasonably clear-cut, there would be little room for controversy. As it is, however, we have no standard by which to provide unequivocal evaluations; besides we are dealing with an issue that transcends purely economic criteria and spills over into the political and social scene."
>
> -Rosegger (1980)

1. A LARGE AND COMPLEX PROBLEM

1.1 Introduction

In this Chapter I shall introduce and outline the theory of "Plural Rationalities". This theory is used to make sense of some controversies about "optimal scale" which were encountered in the course of the literature search and interview work which I carried out as part of the Aston-Warwick Scale Project. This framework is not in the main my own work (although I have contributed to it); it is introduced for the sake of the overall argument, and is needed as a building block for the model to be introduced in Chapter 7.

As stated in the Declaration preceding Chapter 1, the argument developed here has been outlined in different forms in Thompson and Tayler (1986) and in James, Tayler and Thompson (1987a), (1987b).

1.2 Scale and Complexity

The question of scale is, it was suggested in Chapter 1, an extremely complex and multi-dimensional problem. Many factors have to be taken into account when deciding upon the scale of a new plant or factory. Moreover, many of the factors which make the decision particularly difficult are inherently unquantifiable. Whilst economists have paid considerable attention to the concept of economies of scale, and it is certainly true that in many cases an increase in size will lead to savings in capital costs per unit of output, there are many other relevant factors than costs which may impinge upon a scale decision.

Often a "world-scale" plant will embody a measure of novel or innovatory technology- indeed there is a sense in which a change in scale always involves a change in technology. Behaviour near the limits of current knowledge is never entirely predictable and may give rise to major surprises, pleasant or otherwise.

The scale of the production equipment may have implications for the scale of the relevant human organisation, and the way in which it is co-ordinated and controlled. The scale of what may be only one element in the production chain may have implications for the other units in the system, and changes in one may give rise to "system effects" elsewhere. There are less tangible considerations of social organisation and behaviour - how do people feel about working in a very large-scale enterprise or at a giant plant? "Alienation" is one response (as portrayed by Charlie Chaplin in "Modern Times"). Lastly, there may be environmental arguments against building a large plant - because of possible pollution - or there may be arguments against spreading pollution out by dotting small units around the landscape.

The problem is thus far from trivial, involving as it does a multiplicity of considerations and holding a number of ways of making the wrong decision. Complexity and multidimensionality often inhibit precise, quantitative analysis.

1.3 Economic Analysis

Economic theory has a very straightforward approach to the optimum size of the production unit which is embodied in the so-called "U-shaped long-run cost curve". Costs decline until some optimum point is reached, after which they begin to rise again as difficulties of large-scale management (for example) set in. The only difficulty is to find the optimum, least-cost point, which sounds like a reasonably tractable problem.

The U-shaped cost curve has become very popular, featuring in almost every elementary text on microeconomics, and appearing in many other areas besides - for example in production engineering and operations management texts. However, a close examination of the theoretical and empirical foundations of this construct reveal that things are not nearly so clearcut as all the neat diagrams suggest. The evidence tends to show that the U-shaped cost curve is the exception rather than the rule; many cost curves have been found which are L-shaped or J-shaped, and examples can be produced of "W-shaped" cost curves with multiple "optimum" points. Moreover the quality of the econometric data subjected to this kind of analysis has not always been very high, and decisions about the shape of the curve and the position of the "optimum" have been reached on the basis of very few observations. (Refer to Chapter 2 for details.)

Despite the apparent certainty with which many declare their faith in the existence of economies of scale (or, in a smaller number of cases, the diseconomies of scale), the evidence is not always there. Yet there are many true believers, and not merely amongst academics- far from it, in fact. How can this be?

2. SOME PROBLEMS AND PUZZLES

I now briefly describe some problems encountered in studies of large-scale industries. These are drawn both from academic and other published studies, and from interviews which I conducted in the course of the Aston-Warwick Scale project research. The examples have certain things in common: they represent capital-intensive industries in which substantial capital economies of scale are usually claimed; they are industries in which there exists a greater or lesser degree of dissent about the optimal scale of plant; and they number amongst their "dissidents" people who possess considerable and relevant technical expertise in the field. (Interviews are listed in an Annexe to this chapter.)

2.1 Electricity Generation

In most industrialised countries, electricity is supplied by a network of large-scale power stations, whether nuclear- or fossil-fueled. Over the last 30 years especially, engineers have seen the exploitation of "latent" economies of scale as one of the most important forms of technological improvement, and considerable research effort has been directed to this end. Single units with outputs of over 1000 megawatts have been constructed, feeding to enormous power grids, and relying upon a similarly huge intrastructure to keep them running.

Some energy scientists, however, have come to believe that this system has not led to the provision of "least cost" electricity, not least because of the supposed unreliability of the largest units. The inflexibility of a system predicated upon such large individual components has been questioned, and the long lead times and high design and development costs (particularly for the nuclear stations) has led, it is claimed, to serious dynamic inflexibility.

The "Energy Establishment" in the UK does not accept these claims, insisting that "big is best". In the USA some utilities have accepted these arguments, at least in part. Indeed there are some reputable figures in the US energy industry who see the problem of cost reduction in terms completely opposite to the UK CEGB.

> "The replication of a series of identical generating units opens up an entirely new and profoundly different avenue for reducing the capital cost of generating capacity. The economy of scale assumes a new form, and manifests itself as the reduction of cost that can be achieved through the scale

> of operations in replicating large numbers of identical units."
>
> -Fisher (1982)

The economics literature on optimum scale in electricity generation was surveyed in Chapter 2; it was concluded there that plants and systems had been built which were larger by a considerable margin than had been shown to be economically necessary at any stage. It was also pointed out that it is possible to select research papers justifying almost any scale strategy for power production.

2.2 Pulp and Paper Manufacture

The conventional view is that the manufacture of paper requires enormous and very expensive plant, and that scales of output of the order of 100,000 tonnes/year are necessary for competitiveness on cost grounds. Fabio Gobbo, industry analyst, says that

> "The first relevant characteristic of the pulp and paper industry is the existence of considerable technological economies of scale."
>
> -Gobbo (1981)

But this view is not endorsed by the former CEO of Reed Engineering Services Ltd, Mr Arthur Western, who was interviewed in the course of our research:

> "Several manufacturers of paper machines were asked if they could provide information which would enable the optimum machine capacity to be established ... Surprisingly, none of the suppliers contacted could give this information without a costly investigation which they were not prepared to undertake. The assumption was that bigger and faster must be more economic, but no facts to support this assumption were available."
>
> -Western (1979)

Western not only found that the industry could not justify its insistence that "big is beautiful", but came to the conclusion that optimum scale was to be reached at a much lower level- around 35,000 tonnes/year. Modular paper machines should be built to a standard design, which would cut design costs and spread overheads, and result in less production downtime.

Discussions with other people in the industry emphasised that Western and his views are controversial. However, it was generally agreed that his technical abilities were amongst the best and that his knowledge of the industry was first-rate.

2.3 Brewing

The economics literature asserts that the brewing of beer enjoys considerable economies when carried out at a large scale. (Cockerill 1971.) Brewing is often quoted as a classic instance of the economies of increased dimensions and of manpower savings through scale. The existence and importance of these economies of scale were strongly affirmed by members of senior management of two major UK brewers with whom we had discussions.

Yet if there really are these substantial economies of scale, how can it be that the Price Commission report of 1977 found that:

> "large brewers have derived no apparent advantages from larger-scale, more concentrated operations. Their costs and prices are higher and their percentage margins lower than those of regional and small brewers. In other words, the investment of these substantial sums has not improved the position of either consumer or large brewer. This casts serious doubt on how efficient the investment has been."

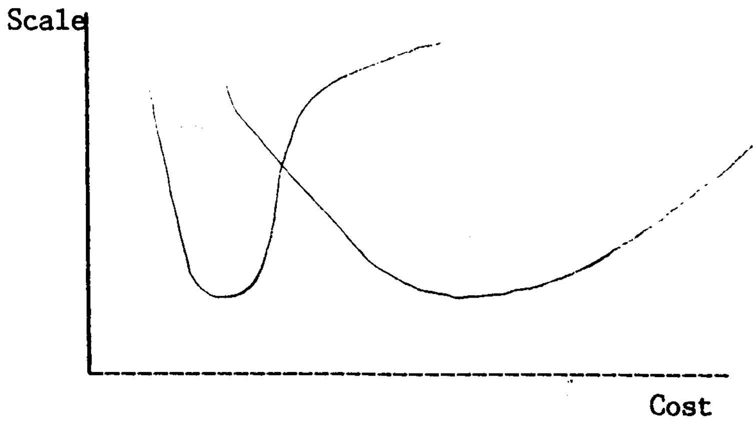
It is also notable that during the 1970s large numbers of "micro-scale" brewers re-emerged, producing beer on a cottage industry scale. This was partly a case of genuine product differentiation: craft brewers filled up the "real ale" niche of the market left by the move of the major brewers into the mass-production keg beer. However, if scale economies are of such crucial importance in this industry, it is puzzling that some producers have survived on annual outputs of under 10,000 barrels when the industry leaders seem to need to build plants with outputs in the millions.

2.4 Cement Manufacture

The cost of producing cement is dominated by the cost of the capital equipment employed. The most important element of capital equipment is the kiln in which the raw materials are fired. Modern cement manufacture in the West relies upon giant slowly-rotating horizontal kilns up to 125m in length. According to the literature and to engineers we have interviewed these are subject to substantial economies of scale, due to the increased dimensions effect.

However a small number of engineers, mostly working on projects for the Third World, believe that the most efficient scale of production of cement is a couple of orders of magnitude smaller. They advocate a return to an older technology involving much smaller vertical kilns. These would be particularly economic, it is claimed, in countries with relatively poor transport or low population density, due to the low value to weight ratio of the product. The scale-cost curves drawn by the two sets of engineers (see e.g. Sigurdson 1977) look something like this:

Figure 2.4.1: Plural Scale-Cost Curves for Cement Manufacture



2.5: Managerial Myths?

These are by no means isolated examples; other instances can be culled from the literature of management adopting definite scale strategies under conditions in which the "objective" technical and economic "facts" were unclear. For example Gold (1974) made a detailed study of scale economies and forces dictating expansion plans in the Japanese steel industry up to the early 1970s. He found that plants were being constructed in significant excess of the maximum size at which scale economies were available:

> "Repeated inquiries concerning why Japanese managements kept approving substantial increases in the scale of blast furnaces despite the absence of strongly supportive technical data elicited several explanations. But their common theme was that the basic drive for such increases was generated in most cases by managerial aspirations."
>
> -Gold (1974) p.10

The role of faith rather than analysis in arriving at scale decisions is implicitly acknowledged by former ICI chairman Sir John Harvey-Jones:

> "One of the things that has gone is the belief in economies of scale... I am a small is beautiful man rather than a big is best man at the moment."
>
> -Harvey-Jones (1983) p.925

It is as if managers have decided to build large-scale production units not because of objective certainty of the economic rightness of this course of action, but through a firm faith in the advantages of size. Harvey-Jones's former "belief" in economies of scale at the time held that status of a "Myth of Scale" - a guiding principle beyond proof or falsity. In Beck's words:

> "There is evidence that in some places the "scientific" approach to decision-making is largely treated as a part of that great institution called the "corporate rain dance". Real decisions are taken as they always have been - on the basis of personal feeling, judgement, nous - and perhaps a measure of bias."
>
> -Beck (1983) p.8

3. RESOLUTION OR RATIONALISATION?

What can be made of these cases? How can it be that experts hold such differing and apparently incompatible views on the optimal scale of operations in their industries? How are we to resolve the dilemna of choice in such situations, when there do not even seem to be overlaps between the margins of error of estimate between the protagonists? It may be that we will do better by avoiding a decision between the different points of view, and choosing instead to look at the problem in a different way.

"Classic" O.R./Decision Theory methodology says that we should list all alternative policies, and select the preferred option from among them by using some clearly-defined (ideally, quantifiable) choice rule. But here there is considerable debate about what the alternatives actually are, and what weights should be attached to them. Moreover different actors sometimes have very different choice rules; e.g. environmental groups regard cost considerations as only one of a range of relevant criteria in assessing power station proposals.

An alternative approach must therefore be taken, and one possible route is to shift the analysis a step further back and to ask, not what result the choice rule prescribes for policy, but what processes have generated the differing choice rules and contradictory certainties about the world in the first place. This is to adopt the idea of "plural rationalities".

3.1 Plural Rationalities

Herbert Simon introduced the idea of bounded rationality - that it is not possible to know everything about the world. People do not see everything - it is as if we go around wearing blinkers which only allow us to see part of the landscape before us, or coloured sunglasses which exclude some colours. The notion of plural rationalities goes a step further. It asserts that there are systematic ways of bounding rationality, so as to perceive certain things and to exclude others. Plural rationality says that there are different ways of including and excluding "facts" from one's vision - as if we had a choice of blinkers, or a choice between glasses which filtered out red light or blue light. Could this be what is going on in managers' and engineers' perceptions of the optimal scale of the production system? It is as if some wear filtering glasses which only allow them to see the advantages of large scale, and others wear glasses which only permit the disadvantages of bigness to shine through. Thus they are aware of (sometimes) completely different sets of "facts", and employ very different evaluation procedures in their appraisal of the "best" scale of operation.

There is a family resemblance between this argument and the use of the Heiner Uncertainty Principle in Chapter 4, which suggested that technology is likely to progress along well-defined and demarcated routes. In this case we are examining the general problem of scale, which, as we have seen, goes well beyond even the difficulties of technological uncertainty. If the Uncertainty Principle is applied again we can see that this very messy question of scale is highly likely to generate strong and firmly-held opinions simply <u>because of</u> the existence of uncertainties. We should expect the emergence of rigidly-pursued scale strategies (which of course will have to be "justified" by deploying suitable technical and economic arguments). The question is, what forms can these scale biases take?

It so happens that there is a ready-made theory which deals in a formal way with the bounded rationalities. This set of concepts comes from the discipline of Social Anthropology, and is know as the "Grid-Group" theory, or the "Theory of Cultural Bias". (See Douglas (1982) for a collection of articles on the theory from its original anthropological context.)

3.2 Alternative Worlds

The theory of cultural bias posits four basic forms of social organisation, known as the Hierarchist, Entrepreneur, Sectist and Ineffectual. (These terms are heavily value-laden; I will often refer to them by using roman numerals only i.e. IV-III-II-I respectively.)

Not only are there are four elementary forms, but there are only four. They are the products of " Grid" and "Group"; crudely, these two variables indicate whether the individual is more or less constrained or has considerable freedom of action, and whether the individual belongs to a collective or not. The four biases may be thought of as the possible answers to two questions: "prescribing or prescribed to?", and "individualist or collectivist?".

I-Ineffectual

The individual who is prescribed to is one who must accept the rationality of fatalism. Passive acceptance of events is matched by an inability (or a belief in an inability) to affect the individual's circumstances. The Ineffectual is found at the margins of institutional formations. Neither resources nor needs can be managed to any significant extent.

II-Sectist

Those belonging to a group which does not have ranks, grades and distinctions must needs be egalitarians. Such a group must have a boundary, and maintain its coherence not only through collective action but also through criticism of those outside that bound. (Hence Douglas's rather pejorative label of "Sectist".) Sects prescribe to non-members. Natural resources are seen as fixed and depleting, so needs must be managed.

III-Entrepreneur

The low-Group individualist operating in pragmatic isolation adopts the market rationality. Everything is negotiable or can be obtained through free exchange and competition. Social exchange occurs via personal networks centred on the individual. The individual's skills and timing are crucial; both needs and resources can be managed.

IV-Hierarchist

The Hierarchist belongs to a highly-structured group which prescribes rules, ranks and distinctions upon its members. Management of the group as a whole, if necessary subduing the needs of individuals to those of the collectivity, is the key to success. Needs are fixed by the Hierarchy, so resources (and the world in general) must be controlled instead. This requires long-term planning and tight organisation, which can lead to the archetypal bureaucratic formation.

<u>Figure 3.2.1: The Four Cultural Biases</u>

		High Grid	
	I - Ineffectual		IV - Hierarchist
Low Group			High Group
	III - Entrepreneur		II - Sectist
		Low Grid	

The usefulness of this typology lies in the fact that there are associated with each preferred form of social organisation a set of views of the world- like the "Managerial Myths" in the case of scale decisions- and cognitive styles. It is these which are of greatest use to our understanding of scale problems, rather than the kinds of organisational forms we look at.

In order to preserve the status quo, each social being has to see the world in a particular way in order to continue to justify his or her preferred form of social organisation and cultural biases. These justifications lead to worldviews which constitute the "cognitive blinkers" referred to above, informing and shaping interpretations of "the facts" of a situation. Conversely, the adoption of a particular cognitive stance or of an impression of how the world is will tend to force certain actions, and hence encourage the adoption of a particular one of the four biases:

I-Ineffectual

Inability to manage one's situation forces passive acceptance. This fatalism in turn encourages the worldview that the environment is essentially random; neither good nor bad, the world is like a "cosmic one-arm bandit". Conversely, the only sustainable response to a truly random world would be ineffectual acceptance.

II-Sectist

A fragile world of depleting resources in which we must tread carefully to avoid upsetting the balance of Nature justifies the permanent social criticism of the Sectist. The need to justify the exclusive boundaries of the egalitarian group, on the other hand, necessitates the discovery of great dangers in the outside world and fragility of the exterior system, reinforcing in turn the urgency of proselytising to the unconverted.

III-Entrepreneur

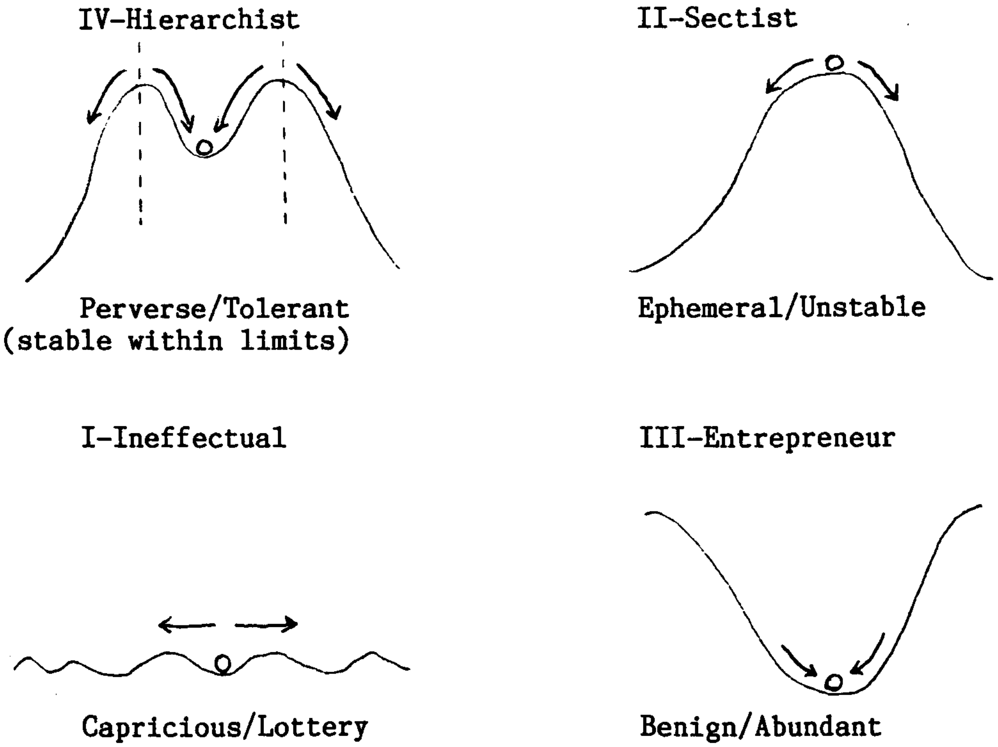
The energetic pragmatic Entrepreneur is hampered by few rules or regulations: everything has its price, and anything is possible given the will and the skill. The world is his oyster; in contrast to the Sectist's pessimism, this worldview optimistically holds that the world is benign and resources are abundant. Again, if the environment of this social actor is indeed highly favourable, then he will be keen to avoid regulations and prescriptions which hamper freedom to take advantage of the abundance, and to adopt an enterprising and exploitative approach to life.

IV-Hierachist

Control is only necessary when there is something to be controlled which has a chance of going wrong. The Hierarchist justification is a world which will yield goods for all if managed carefully, but in which great care must be taken to avoid upsetting any applecarts. This need for care and management extends to social organisation as well, which must be controlled by procedures and rules, and maintained by clear definitions of sub- and superordinations in status.

The views of the world embodied in these plural rationalities can be expressed in yet another way, in terms of "Myths of Stability", by little diagrams of a ball on a landscape. The ball represents the state of the system which the different worldview-holders wish to manage. (The system might be the natural environment, some larger social organisation, or indeed a firm or an industry in a commercial setting.)

Figure 3.2.2: The Myths of Stability and the Cultural Biases



In the III-world of the Entrepreneur the ball is in the bottom of a bowl, and however it is disturbed, it always returns to rest at the same place eventually. This is global stability. The reverse is true of the II-world of the Sectist, where the least disturbance will consign the ball (and the system it represents) to oblivion. The I-world of the Ineffectual has no macro-structure; disturbances may produce better or worse results, but the outcome is indeterminate. The IV-world is a combination of II and III: stable within limits, and unstable if control is lost and the ball/system strays beyond the prescribed area.

The following Table 3.2.1 sets out some of the characteristics of the cultural biases, showing (1) the preferred or typical pattern of social origin, (2) attitude to scale, (3) dominant form of rationality, (4) attitude to natural resources, (5) preferred system characteristics, (6) strategies for dealing with power, and (7) games (in Von Neumann's sense) in which they play:

Table 3.2.1: Characteristics of the Four Cultural Biases

IV-Hierarchist	II-Sectist
1. Nested (hierarchical) bounded group	1. Egalitarian bounded group
2. "Big is Best"	2. "Small is Beautiful"
3. Bureaucratic	3. Egalitarian
4. Resources can be managed for the benefit of all	4. Resources can only be depleted, and therefore conservation is essential
5. Systems must be designed for maximum controllability	5. Systems must be designed so as to have the least vulnerability
6. Centralisation	6. Decentralisation
7. World is a positive sum game (within limits)	7. World is a negative sum game

I-Ineffectual	III-Entrepreneur
1. Marginal	1. Ego-focussed network
2. Scale is imposed	2. "Appropriate" Scale
3. Passive and Fatalistic	3. Pragmatic and Exploitative
4. Resources are a lottery, appearing and vanishing randomly	4. Abundant resources can be harnessed through skill and effort
5. Systems are inherently chaotic, but ideally they are designed for "copeability"	5. Systems must be designed for flexibility and fluidity
6. Marginalised	6. Networking
7. World is a zero sum game	7. World is a positive sum game

It is clear that the systemisation of worldviews drawn from the Grid-Group theory can be applied more generally than just to look at individual's biases. Wider attitudes and preferences may be studied with the aid of these insights. The theory has been applied recently to the analysis of a number of problems in applied systems management, including: disposal of hazardous waste, the risks involved in the siting of liquefied natural gas plants and other forms of risk (Douglas and

Wildavsky 1982); official policies towards poverty (Thompson and Wildavsky 1986a); information processing in organisations (Thompson and Wildavsky 1986b); the management of the Himalayan ecosystem (Thompson, Hatley and Warburton 1986); the criticism of energy futures modelling (Thompson 1984); and attitudes to environmental policies (James, Tayler and Thompson 1987).

These studies demonstrate the versatility of the theory as an explanatory metaphor for plural rationalities when applied outside its orginal territory of social anthropology. Similar fourfold typologies have been employed by other researchers; a good popular example is Handy's "Gods of Management" (1985), which indeed shares a common intellectual ancestry with the Grid-Group classification. A different but analogous fourfold model which converges with that of Douglas has been taken up by a number of social psychologists and management writers, particularly in the USA (e.g. Mitroff and Kilmann (1978)), at least partly inspired by C.G. Jung. (He in turn possibly obtained the schema through study of the Hermetic tradition - the Medieval alchemists.) The recurrence of similar or identical fourfold patterns is a fascinating motif - see Tayler (1985), where the analogies between many such fourfold patterns are analysed.

4. AN EXAMPLE

How does all this help? An immediate (and conveniently clear-cut) example is afforded by the contrast between the CEGB and the environmentalist group "Friends of the Earth", who are excellent examples of the Hierarchist and Sectist biases respectively. The former is a structured, monolithic bureaucracy, the latter a left-leaning, anarchic/democratic group. The CEGB has a very firm line in favour of large scale, centralised production units, whilst the environmentalist groups believe in small-scale, decentralised plants which need far less infrastructure. (They are also passionately opposed to nuclear developments, of course.) The CEGB is a purveyor of official optimism whilst stressing the need for long-range planning, whilst FOTE constantly warn of the dangers of making long-term assumptions about, say, the safety of nuclear waste dumps.

These polarities are all aspects of the same thing, and it should be stressed that they constitute an interlocking system of beliefs which depend upon, and are sustained by, one another. The cultural theory shows why the one group perceives the advantages of large scale power systems in one way, and why the other sees only the disadvantages. The very elements which the environmentalists criticise - capital intensity, large scale, inflexibility, heavy infrastructure demands - are the very things which the CEGB policy analysts see as desirable, leading as they do (in their eyes) to an "optimised" energy supply. The environmentalist criticism of lack of resilience does not start from the same premises, and is indeed quite outside the worldview of the UK utility planners.

This analytical framework allows us to begin to understand the fundamental differences of opinion which are found about the value of large or small scale production systems. Of course not every situation which is encountered - indeed not all of the examples recounted above - is as straightforward as the energy debate, because real-life industry decisions are not taken against a background of dispute between such obviously different institutions as the CEGB and FOTE. The cognitive aspects of the four biases are much more important than the social forms in which they are enacted, in general.

This example illustrates the scale biases of two of the worldviews. The Sectists are inclined towards small-scale technological solutions, and are cautious towards "Big Science" and high technology. The Hierarchist tends towards large-scale organisation, so large-scale technology presents no problem, and indeed provides a justification for maintaining centralised and rule-governed social systems. It also matches the tendency to control and to forward planning. The Ineffectual can have no significant scale biases, whilst the Entrepreneur is happy to examine any possibilities that are presented. This openness to novelty means that technological innovation is particularly welcome to the Entrepreneur.

Table 4.1: Scale Attitudes of the Four Biases

IV-Hierarchist	Favours large scale projects, adopting a long-term optimising approach
III-Entrepreneur	Favours technical change and "satisficing"-whatever scale is most convenient
II-Sectist	Suspicious of large-scale projects and high technology; takes a more cautious path
I-Ineffectual	Has little chance to express preferences, and will employ strategies at random

Of course, when applied to the management worldviews of competing industrial companies, the biases are not so all-encompassing as in the case of the CEGB-Environmentalist debate. In the latter case the differences of perception are based upon very deep and fundamental social and political (and, in some cases, quasi-religious "Nature Mysticism") views. In applying plural rationalities to management decision-making it must be recognised that these more universal values will be to a great extent common to all participants, and the differences between them will extend only to those things which form the basis of competition: the production technology, the design of their organisation, their long-range planning and assumptions about their business environment, and so on. Thus a very cautious, small-scale oriented enterprise could be identified with the II-worldview, and a firm which aims to control the market by confidently constructing giant production plants most naturally associates with the IV-worldview.

5. CONCLUSIONS

Although there is a considerable body of accepted wisdom about the economies of scale, and firm beliefs about their existence in the industries we have studied, there is nevertheless some appreciable room for dispute. People with substantial technological and commercial expertise, some of them at very senior levels in their industry, can be found to have contradictory views about the optimum scale of production.

Instead of immediately trying to resolve the conflicts in favour of one side or the other, it is interesting and useful to approach the problem from a perspective of plural rationalities. This perspective explains the differences of opinion over "the facts", and allows us to think in a structured way about the possible alternatives. The "Grid-Group" theory from social anthropology provides a useful tool for understanding the plurality of views about "optimum" scale. It also facilitates explicit modelling of different worldviews and scale biases in a more detailed and realistic model of the evolution of scale.

ANNEXE: SELECTED INTERVIEWS ON SCALE FOR ASTON-WARWICK PROJECT

PAPER

Mr Arthur Western, formerly CEO, Reed Engineering Services Ltd: 18/3/86.

Dr Roger Grant, Consultant: 9/9/86.

Mr Colin White, Business Development Manager, Paper Industry Research Association (PIRA): 9/5/86.

Mr E R Palmer, Head, Pulp, Paper and Fibres Division, Tropical Development and Research Institute, ODA: 30/7/86.

BREWING

Mr Roger Lowe, Production and Distribution Executive, Allied Breweries: 4/6/86.

Mr D Randall, Systems Development Director, Allied Breweries Management Services: 25/2/86.

CEMENT

Mr R J Gates, Techncial Director, Rugby Portland Cement Co.: 5/11/85.

Dr D Watson, Head of Blue Circle Technical, Engineering and Process Division: March 1984.

Chapter 7: EMIR- An Evolutionary Model of Increasing Returns

> "Instead of building a model of a particular system in terms of the salient features of the moment, it may be more informative to study generic models and the way that their constituent elements cluster, grow and structure according to the series of "folds" that their interactive mechanisms impart to them, and the attributes which emerge for different branches of solution ... a good model must be a metamodel"
>
> -Allen et al (1985)

1. INTRODUCTION

In Chapter 1 it was argued that the application of "traditional" methods of analysis based upon an imitation of the methods of Victorian science was inappropriate to the complex "problems of scale". A particular example of such reductionist methods was examined; the orthodox economist's account of the economics of scale and of increasing returns was found to be lacking. Among the reasons for this were the difficulties of reconciling the theoretical constructs of equilibrium analysis with the realities of genuinely "increasing returns" due to the existence of economies of scale and the possibilities of technical change. ("Increasing returns to scale" means that greater benefits accrue the greater the scale of operations. Economies of scale are an example, where costs of production per unit reduce with increased scale.) It was also seen that bounded rationality and plural rationalities would have to be taken into consideration in any superior description of the evolution of scale.

First of all, a new description or model must go beyond the confines of a static equilibrium approach. Secondly, it must incorporate the findings of the considerable body of empirical research on scale reviewed in the second section of the thesis. It must have a reasonable representation of the evolutionary process of technical change, not leaving it out as some exogenous variable. The new model must also be able to encompass a portion of the available plurality of worldviews and strategies available to the economic actor, not assuming away the very important human and cognitive factors in the scale process. Finally, any improved description must allow us to ask questions of it, and ideally permit experiments to be conducted with it. This chapter introduces the new model.

1.1 Objectives

The objectives in devising this new model are therefore threefold, and correspond to three distinct interests:

1) The theorist wishes to have a theoretical framework which is more in tune with reality, and which will stand up despite the abandonment of fifty years' worth of microeconomic assumptions;

2) The policy analyst wishes to know "Why do things (firms, production units, plants) become big?" The (neo-classical) theorist's answer has been "It must be because big is more efficient" - but it is not clear that this conclusion is not just the consequence of the old assumptions.

3) The decision-maker wishes to know what to do next. Can a new model produce better decisions, by giving new insights into the dynamics which lead to particular industry structures?

1.2 Summary

The structure of EMIR ("Evolutionary Model of Increasing Returns") is set out in detail in the next Chapter. The following is a brief overview of its structure and function.

The model consists of a number of firms building production units to meet future demand. The key element of the simulation is the decision to build capacity; this involves a choice of scale, a forecast of the future, and a selection of technology, all modified by the decision-maker's worldview. New capacity may be added to meet excess forecast demand, or to replace old capacity made inferior through technical change, or a combination of the two.

The price received for output depends upon relative supply and demand, demand being the only exogenous variable in the model. Different demand scenarios can be run through the system. Production units have an initial capital cost, and incur other costs when they are operated. Plants do not last forever; after ten periods (years) have elapsed, they have a small probability of being written off in each subsequent year.

Firms may run up debts in order to build new capacity, and will have to pay interest charges if they do. Firms making profits are assumed to pay dividends. There are limits to allowable gearing ratios i.e. debt to asset value proportions. If a firm has no plant operating and has substantial debts then it is declared bankrupt and disappears from the simulation.

The production technology employed may change. Firms search for better techniques, and may also try to increase or reduce the possible scale of plants they build in the future. Technical change is a search procedure within limits (as set out in Chapter 4). Most technical change is incremental, but it is possible to set the model so that on rare occasions completely new technologies are discovered. Technology is not a free good, immediately and costlessly available to all economic actors; it is "owned" by its discoverer, and embodied in its owner's production units.

Production technology is defined in the model by a set of "co-ordinates" (K,L,V,MAX,MIN) which state what kind of production plant may be constructed. The size of a plant must lie between MAX and MIN. The initial capital cost of building the plant depends upon K, and the costs of operating it upon L (which determines fixed overhead costs) and V (which sets vriable cost per unit of output). Firms improve their technological possibilities by searching for new sets of co-ordinates which will either allow them to build bigger plants (larger value of MAX), build plants more cheaply (lower value of K), run them more cheaply (smaller L or V), or some combination of these.

Firms' behaviour, both in the innovation search process, and in their reactions to their forecasts, performance and competitor's actions, are partly conditioned by their "worldview". There are four possible worldviews in the model, and they are embodied along the same lines as in the "Surprise Game" (Thompson and Tayler 1985). The worldviews have been introduced and discussed in Chapter 6. In the experiments to be discussed in the following Chapters, only two of the worldviews are used (the II-Sectist and IV-Hierarchist).

1.3 Nelson and Winter

This model is in some ways similar to those of Nelson and Winter (1982). Indeed, it was inspired by their bold step out of the traditional economic mainstream in an attempt to provide realistic economic theories of technical change and development. The approach taken here is intended to be in sympathy with the spirit of Nelson and Winter's "Evolutionary Economics". However, EMIR is more ambitious than any of the models yet described by these two pioneers: they have not tackled the problem of economies of scale with respect to plant size, they do not deal with competing strategies or "worldviews", and their descriptions of technical change as embodied in the models are (perhaps intentionally) less complex than those employed in EMIR.

Figure 2.1: EMIR Business Cycles

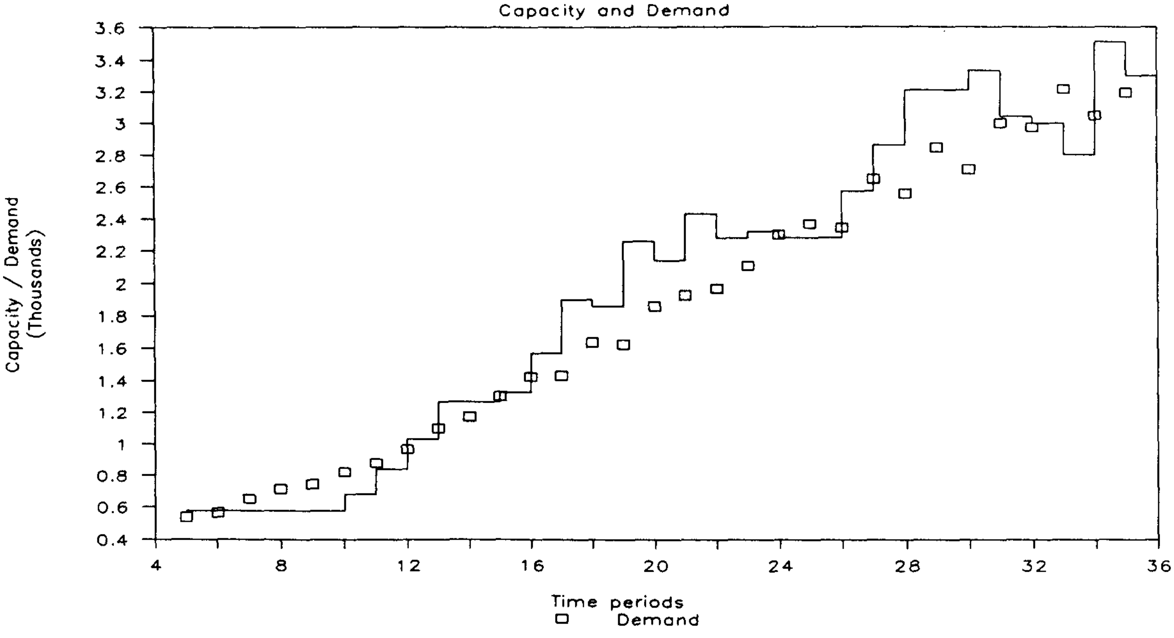
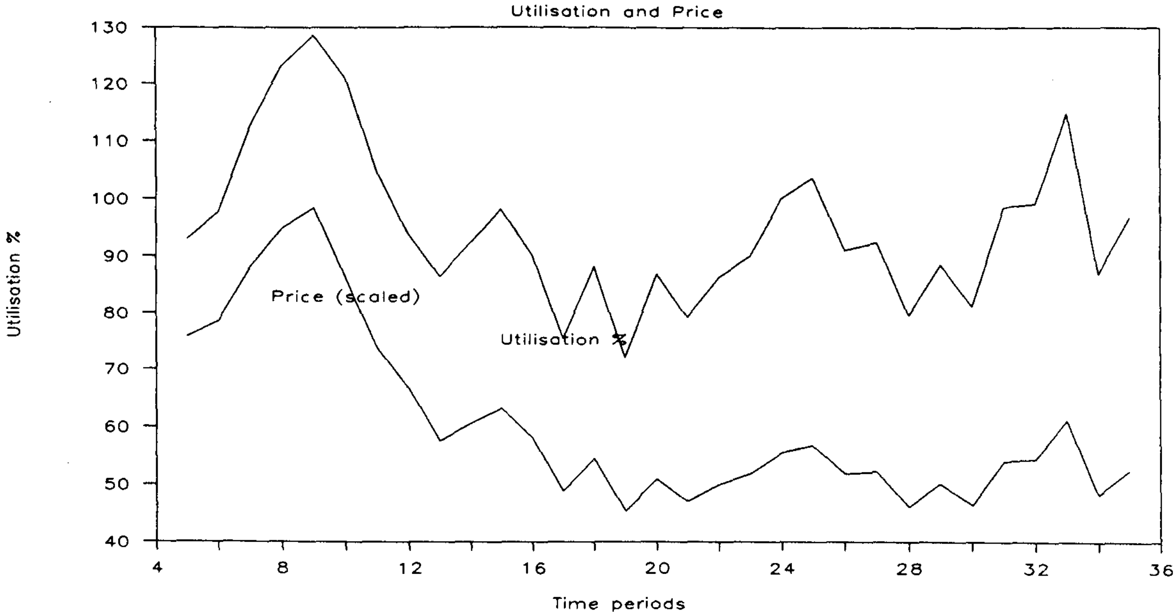


Figure 2.1: EMIR Business Cycles



2. APPRECIATIVE DESCRIPTION

In Chapter 9 a series of experiments with EMIR is described. For the rest of this chapter we will concentrate on the qualitative aspects of the model.

"Appreciative description" is Nelson's phrase for a description which incorporates those features of a situation which accord with real life. Not necessarily very technical, this kind of description is concerned with realistic qualitative behaviour of a system- for example, do our model firms behave in a way which might be recognised by businesspeople who are not economists (as opposed to satisfying the rigorous but unrealistic constraints of the theoretical economic description).

First of all, consider a short-term "cycle" of behaviour displayed in the model. There is a constant cycle of short-term dynamics, based around the interaction of supply, demand and price. (See Chapter 8, section 3.1 for details of the pricing model.) Figure 2.1 shows, for part of a simulation run, the way that short-term cycles occur in the model.

Figure 2.1 shows periods of high and low utilisation, which lead to relatively high and low prices. The utilisation is driven by forecasting of demand, which sometimes overshoots and sometimes undershoots. However, as can be seen from the plots of industry capacity and market demand, the deviations of supply from demand are continually being remedied by either ordering of new plants, or retiring of surplus capacity. For example, the industry at t=5 has too little capacity; this is remedied by significant additions at t=11, 12 and 13. At t=17 too much capacity is available; a small amount is retired at t=18. At t=24, t=30 and t=33 random plant failures probably account for the capacity reductions. The cycle of causality runs: "High utilisation leads to high prices. High prices encourages investment in new plant. Addition of new plant reduces prices. Low prices make some plants unprofitable. Unprofitable plants are retired. Removing capacity leads to high utilisation."

A description of the model's long-term behaviour could be pitched at a number of levels. Here I will concentrate on the growth process, of firms and of technologies. "Increasing returns" could be crudely expressed as "The more you have, the more you get". This is indeed an important feature of EMIR.

The firms begin the simulation run in an identical state - all have the same capital and the same kind of plant, and possess exactly the same technological capabilities. After only a few time periods, however, the first asymmetries occur - a new plant is built by someone to meet an anticipated increase in demand. It may be that the new plant is larger than the pre-existing ones, or that it embodies some slightly superior technology. Sooner or later one or more of the firms attains some kind of cost advantage over the others, through economies of scale or through improved production technology.

When this happens the industry begins to take on a dynamic all of its own. The superior firm(s) are more likely to be able to build plants than their inferior competitors. This is because they are more profitable and are therefore less likely to be constrained by a large debt; because, perhaps having built more production units already, they have acquired some superior technological capability ("Learning through Doing"); or because they have built more plants and therefore have a large market share, which can be rationalised by the construction of a single giant plant which will reap substantial economies of scale and further improve the firm's cost advantages.

This process continues; those who have more are able to build more, further improve their technology (because it is necessary to build a unit to discover the true parameters of a novel technique), and further reduce their costs (thus improving their profits). Meanwhile, the remainder are constantly being pre-empted by the superior firms, who can accept lower levels of prospective capacity utilisation. Thus they rarely get the chance to build, so their own technological improvements are few and far between, and market share drops, giving fewer opportunities for "economy of scale" rationalisations. Old plants begin to fail through the age effect, and, as the industry average production cost falls, so does the price level. The inefficient firms lose their profit margins, and in some cases begin to operate at a loss.

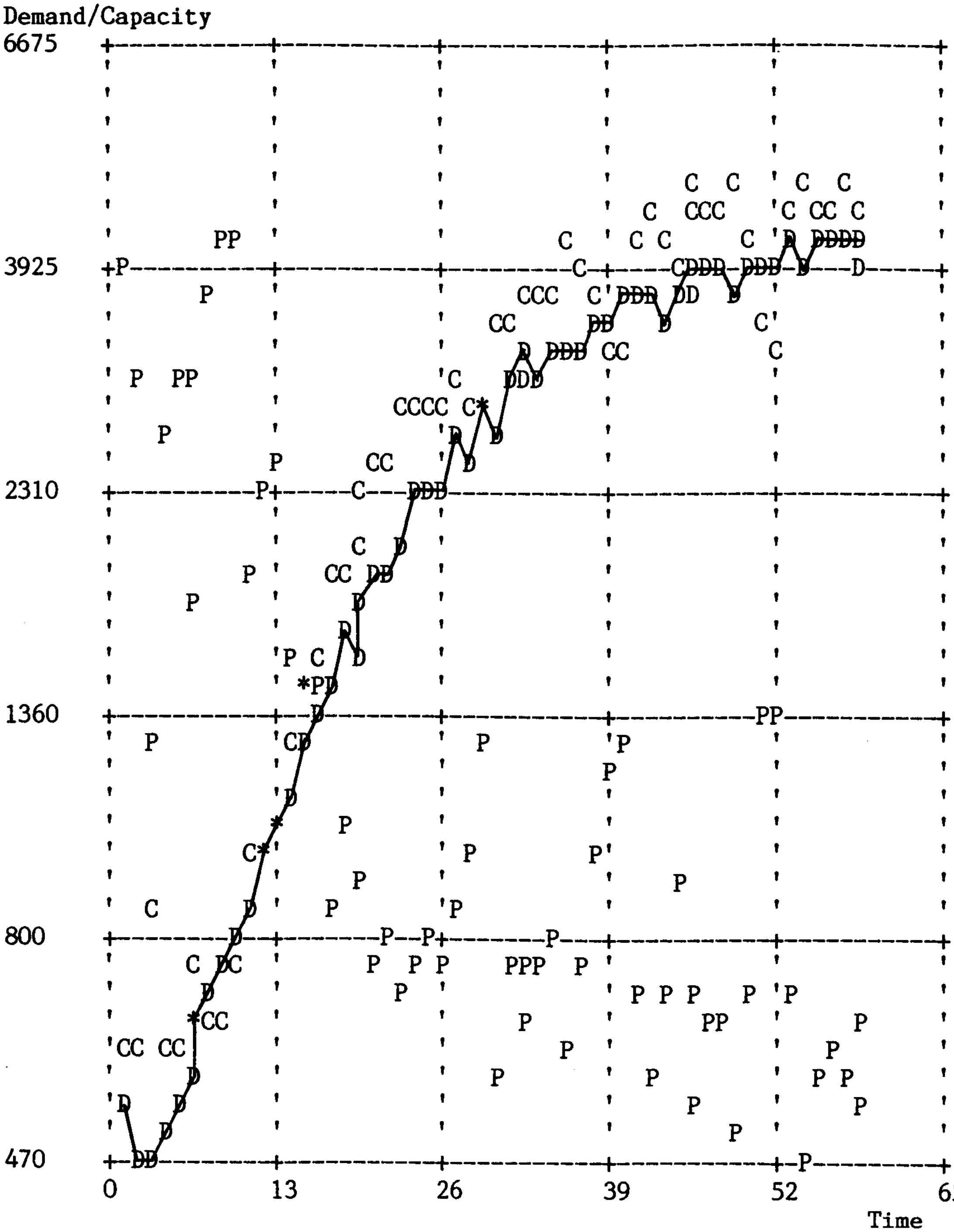
Two things can happen to the weaker firm. The most drastic is bankruptcy. The firm may have taken on a large debt in order to finance its capacity, but low margins mean that it does not even cover interest repayments. This will further reduce its ability to introduce new or larger units. Eventually its existing capacity will be retired, either through old age or, more likely, because it is unable to make a profit on operating its production units. The weight of debt then produces insolvency.

Alternatively, the firm may escape the debt trap, though nevertheless sustaining losses. It becomes non-operational for a while, having no production units but carrying little or no debt. Its salvation will come through imitative innovation, since unprofitable firms can try to copy the techniques of the most successful. Thus the survivors of the competitive process acquire some of the advantages of the winners, and successful technologies are diffused throughout the industry.

This pattern is even more pronounced if radical innovations are discovered. A really good novel technology brings about what Schumpeter called "gales of creative destruction". The existence of a large cost advantage for the new technology means that its owner can build new capacity almost at will. As new units are introduced, they begin to undercut severely the rest of the industry; previously highly successful firms, committed to the old technology, lose money and market share. In extreme cases the industry is completely taken over by the innovating firm for a while, until others learn to copy the new technique of production.

The following diagrams and graphs may give some idea of the typical industry dynamics from EMIR; they refer to simulation run 16HTC4IV (a run similar to the experiments described in the following Chapters). They show time series data for demand, capacity and price (Figure 2.2); firm total capacities over time (Figure 2.3: NB vertical scale is logarithmic to better display proportions); firm sizes by Capital value (Figure 2.4); and each firm's average production cost over time (Figure 2.5).

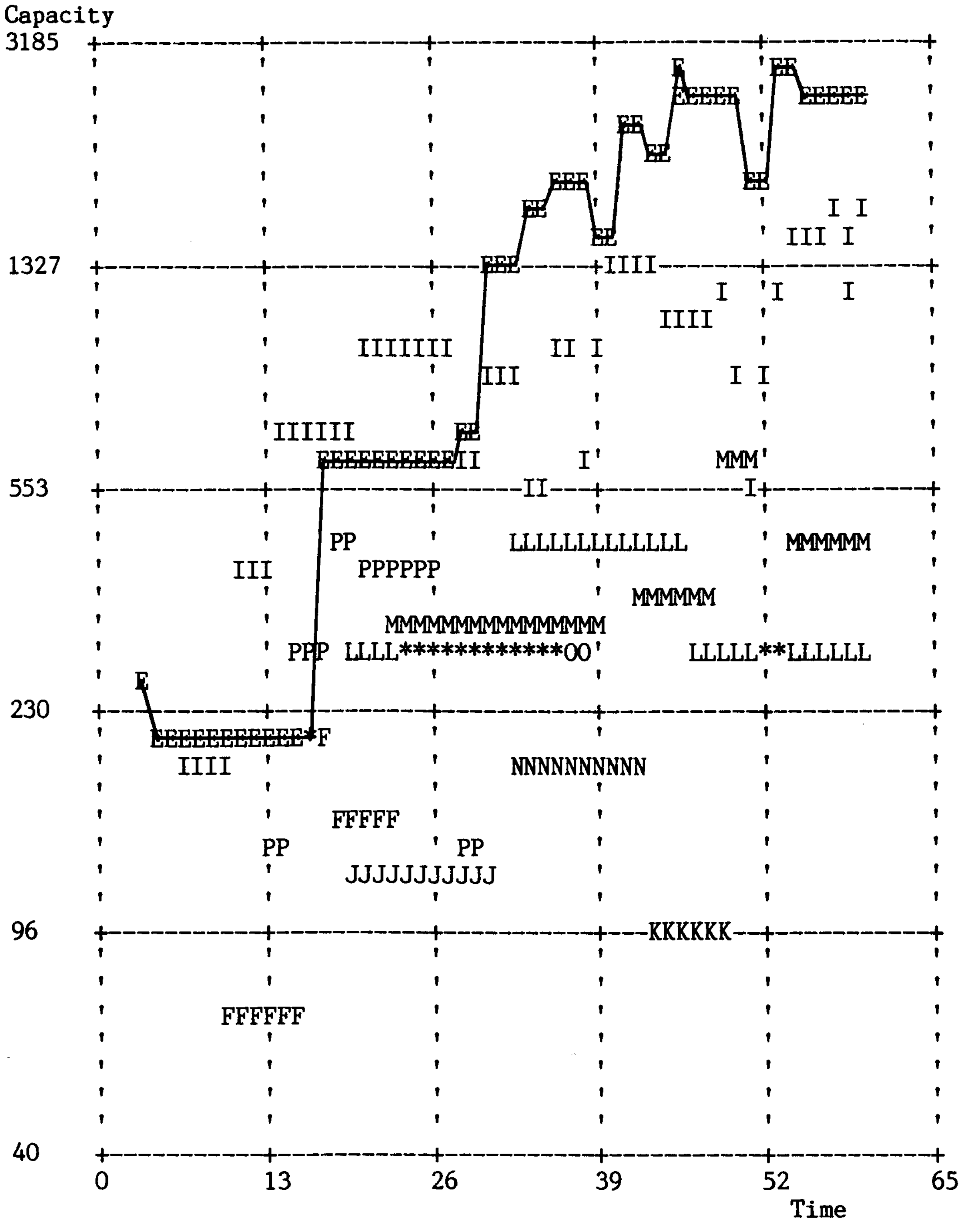
Figure 2.2: Industry Demand, Capacity and Price for run 16HTC4IV



D = Demand
C = Capacity
P = Price

NOTE: Price (P) fluctuates as a function of utilisation

Figure 2.3: Total Firm Production Capacities Over Time for run 16HTC4IV



Note that Figure 2.4 was produced by a different program from the others, so that letters identifying firms in the plots do not all correspond; firm "E" is the same in all three, however, and has been highlighted in the graphs.

Figure 2.4: Firm Sizes by Capital Value over time for run 16HTC4IV

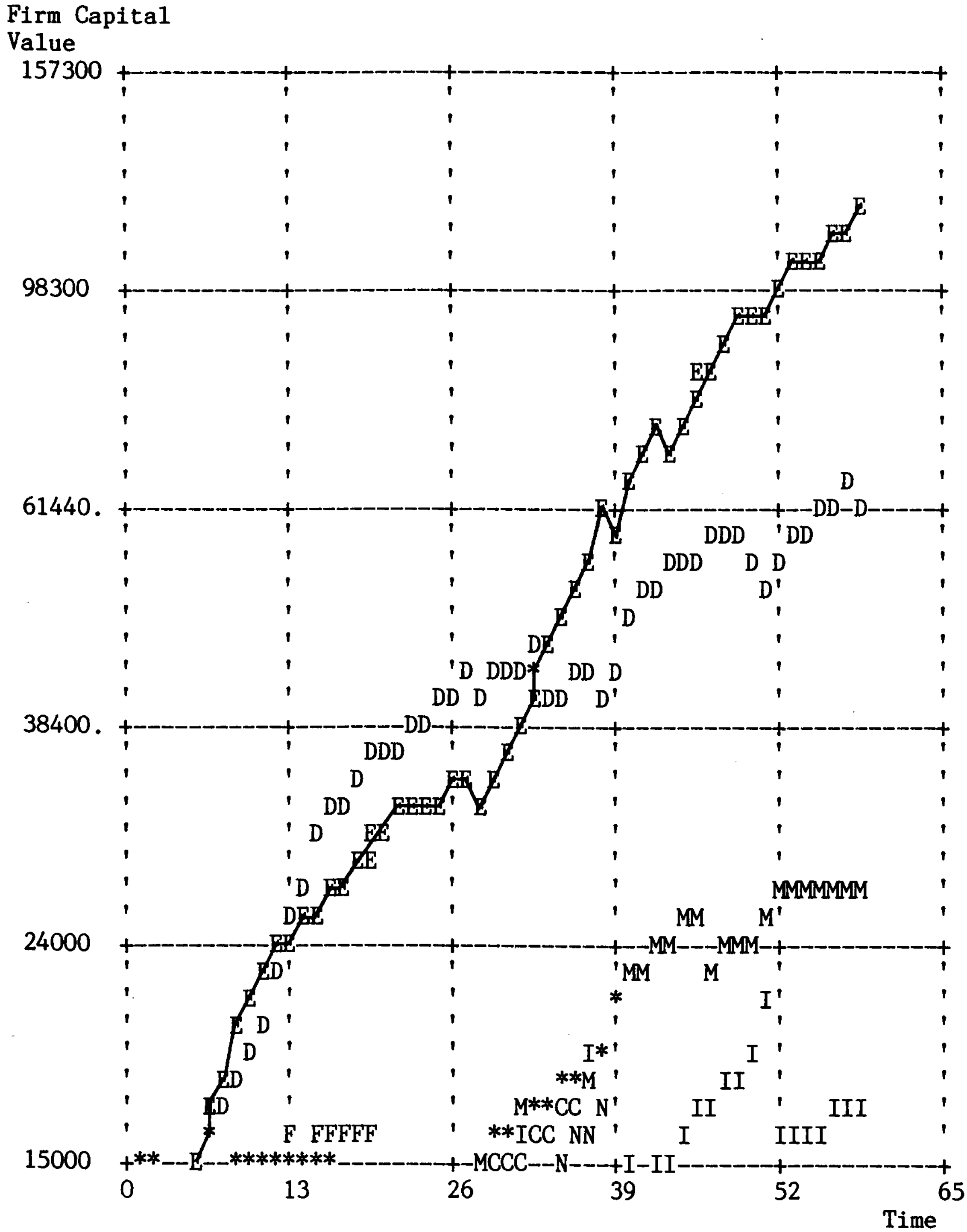
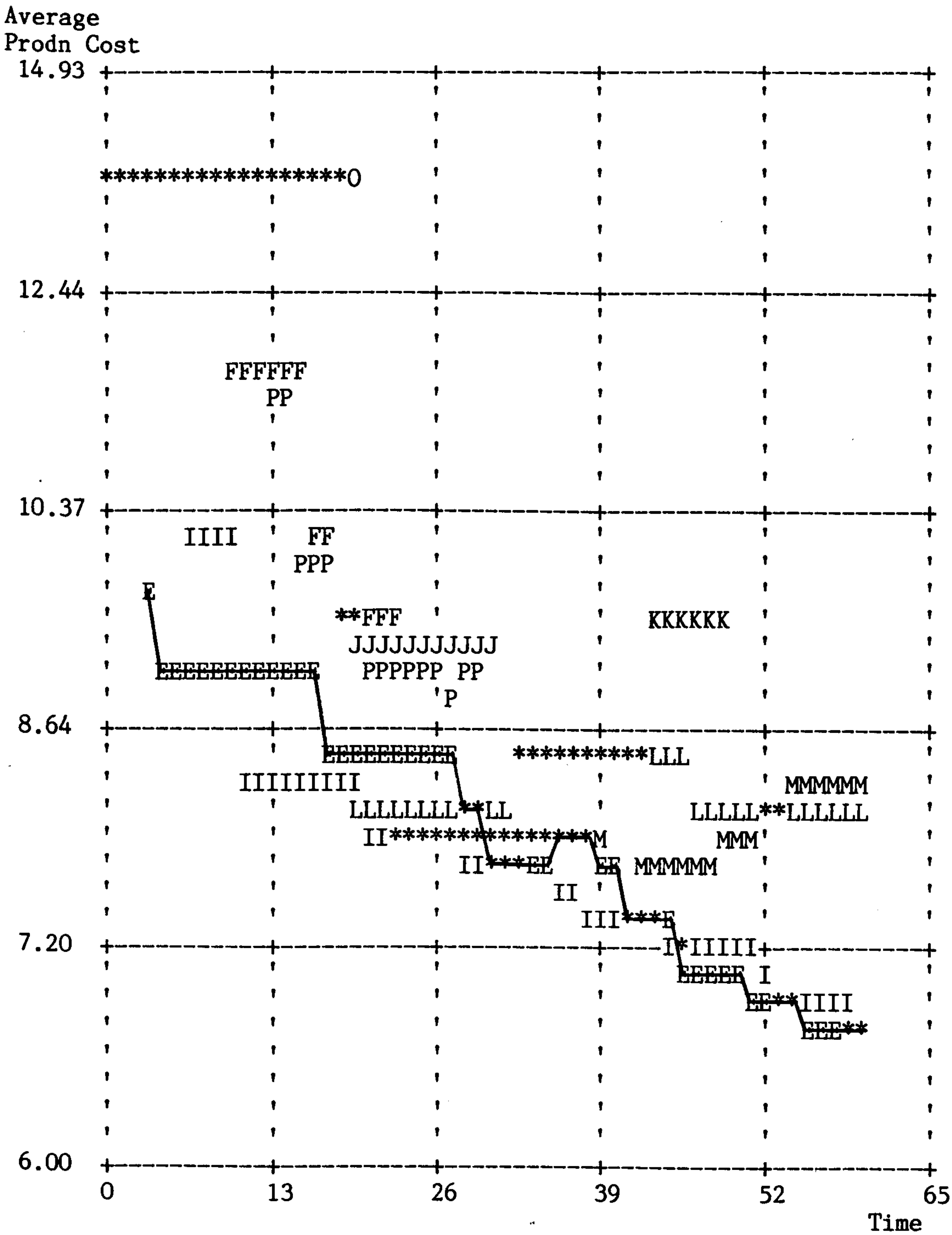


Figure 2.5 shows that the average production cost of firm E seems to follow very closely a traditional "Learning Curve" of improvement over time. (Remember the vertical scale is logarithmic.) This interesting finding is by no means unique amongst the simulation runs; indeed it is quite common to find the more successful firms demonstrating apparently "law-like" patterns of steady development. More could be said on this

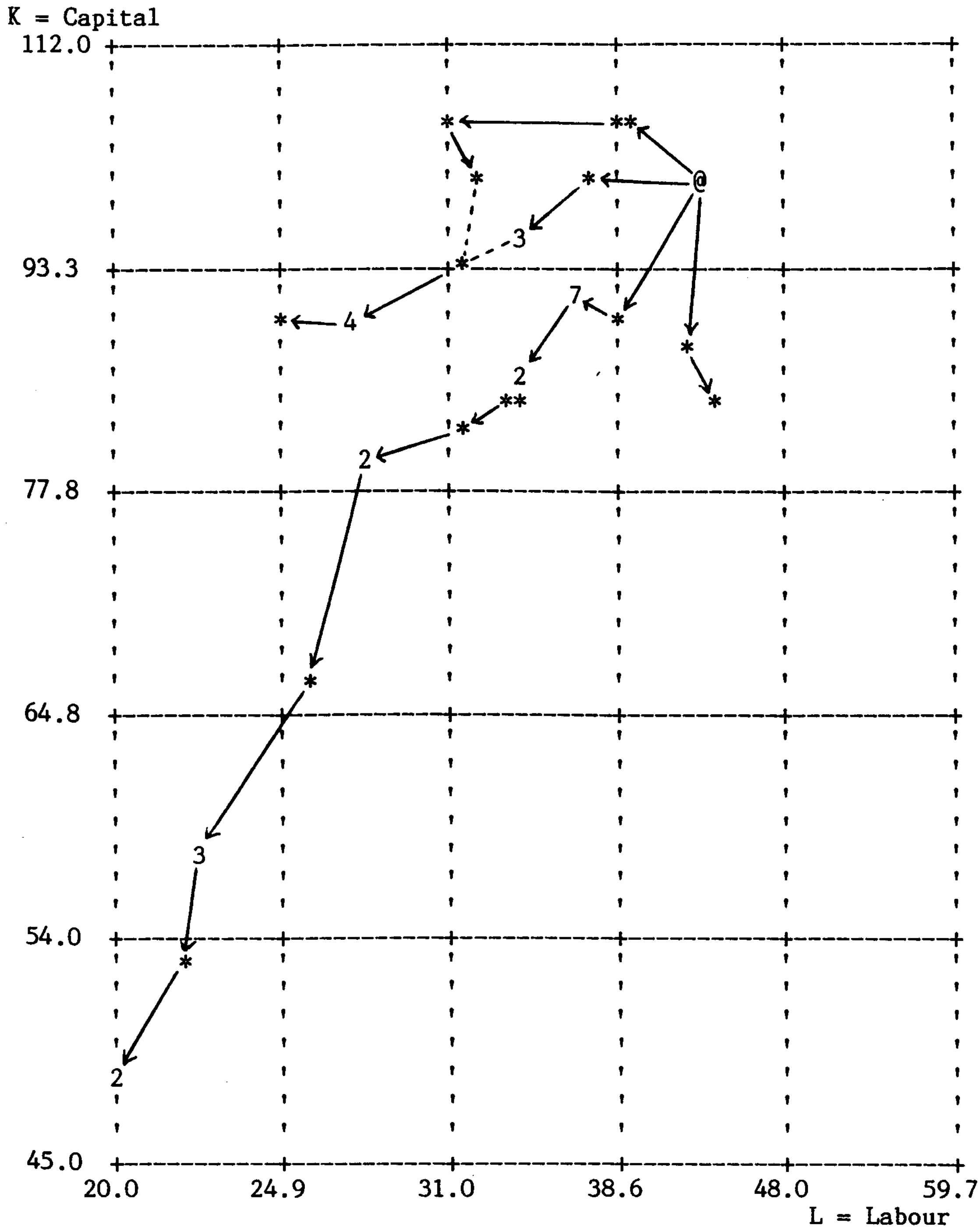
point; for the moment I will merely note that cost reductions have been achieved by E with the help of economies of scale as well as of traditional "factor shares" technical improvements. This is not uncommon in real life; see Dutton and Thomas (1984), page 240.

Figure 2.5: Firms' Average Production Costs over time for run 16HTC4IV



The development of technologies has been described almost as if they had an independent life of their own, and in a sense this is so. The development of a technology (again from 16HTC4IV) is given in Figure 2.6 by a plot of K and L coefficients (note log-log scale). All firms begin

Figure 2.6: Technological Coefficients (K and L) for run 16HTC4IV

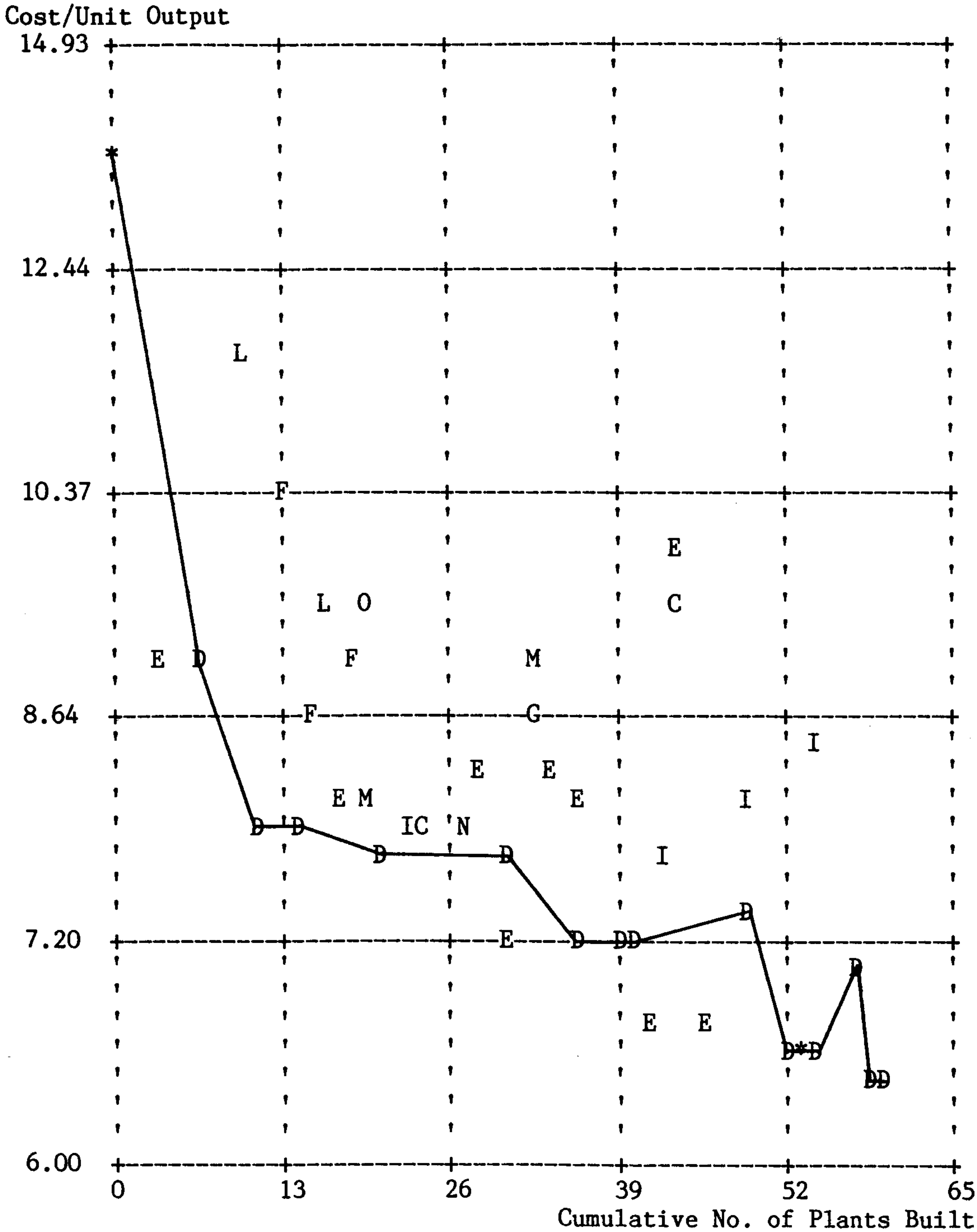


NOTE TO FIGURE 2.6: Numerals indicate multiple occurences of a technological pair (K,L). "@" is the starting technology. Refer to Chapter 8, sections 1.3 and 2 for description of technological specification and the innovation process respectively.

with the same production technology (K,L) = (100,50). Definite trajectories of development appear to be manifested; in this case innovation is initially in the direction of saving on labour costs (moving right to left), but as the industry matures development goes in the direction of lowering capital needs. Some abortive development paths are not pursued; one wins through to bring about considerable cost savings, roughly halving both K and L.

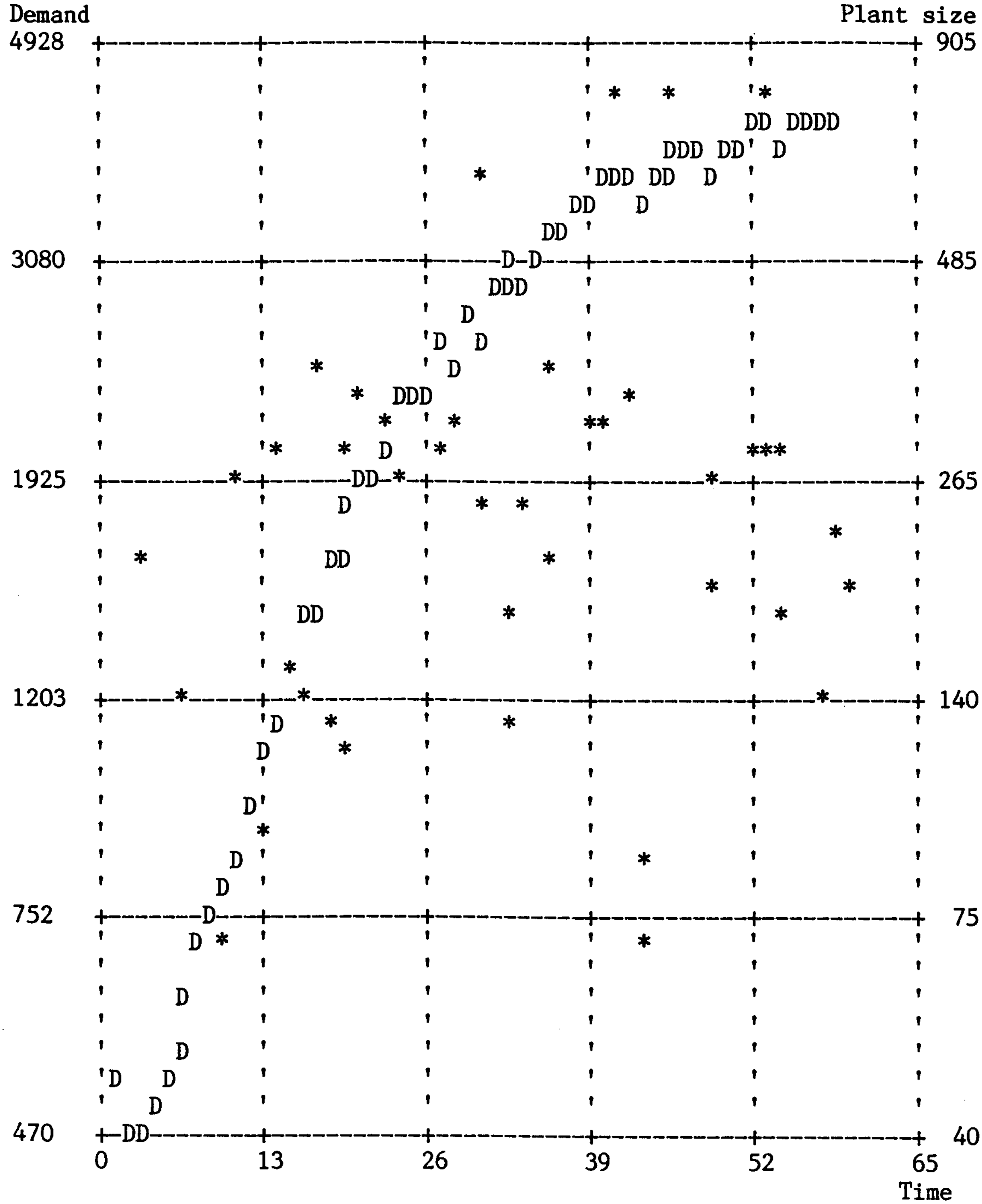
We can go further and produce "learning curves" or "progress functions" for production costs. Fig. 2.7 plots the cost of making a single unit of output against cumulative numbers of production plants in the model industry; this log-log graph is highly indicative of the typical learning curve relationship. (The successive plants of one particular firm are highlighted on the graph.) In this case, production costs per unit of output steadily decrease as more plants are built.

Figure 2.7: Prodn Cost (per unit output) of Successive Plants for 16HTC4IV



Similarly we can see that maximum plant scale follows a fairly regular development pattern; Figure 2.8 plots the sizes of plants constructed over time compared with the total market demand. (Log plot of size and demand again.)

Figure 2.8: Plant Sizes and Industry Demand over time for run 16HTC4IV



D = Demand
* = Plant

At the macro-level, these last three Figures (2.6-2.8) in particular are of great interest, for they suggest that EMIR has produced certain macro-regularities (forms of self-organisation?) which have been noted by many observers. Figures 2.6 and 2.7 relate to "Progress Functions" of different kinds, whilst Figure 2.8 gives at least a hint that maximum

Fig 2.9: Plant Size & Demand

US Basic Steel

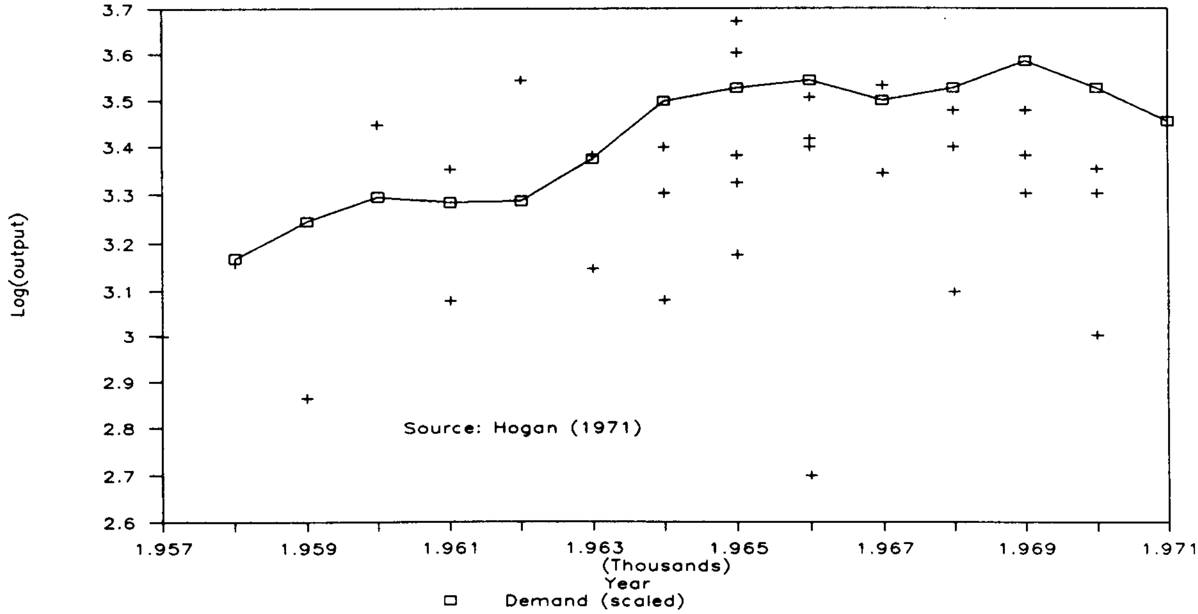
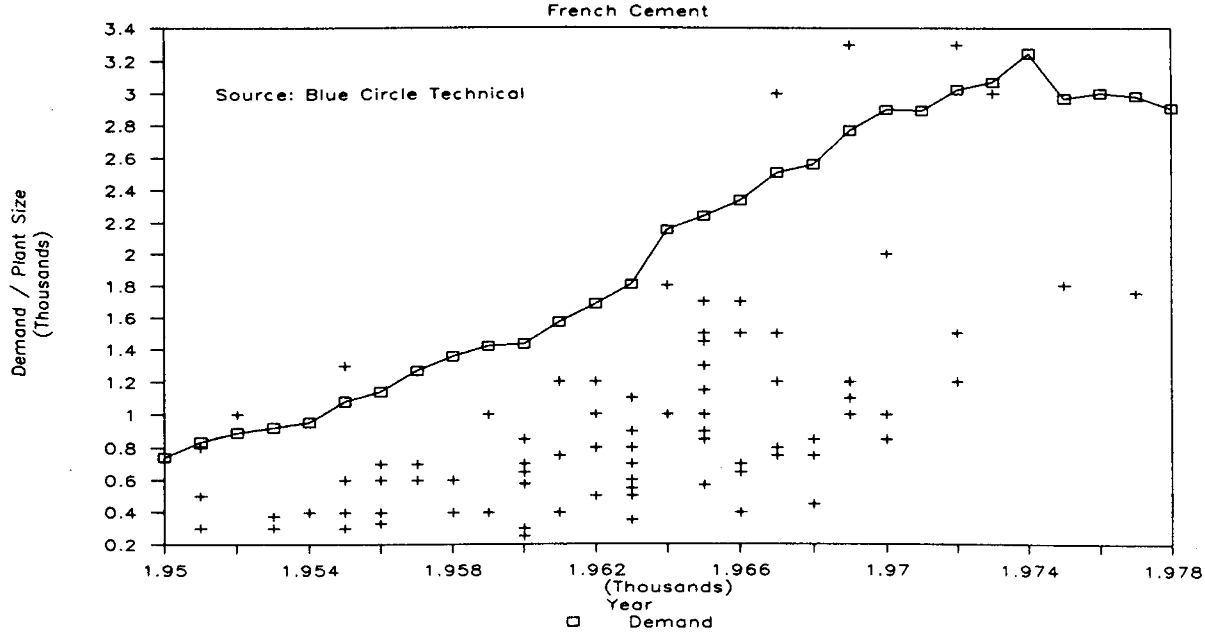


Fig 2.10: Plant Size & Demand

French Cement



plant scale at any time is related to overall industry size. This latter relationship is not so well-established as the learning curve; it is examined by Simmonds (1969), Martino and Conver (1972) and Sahal (1982). Compare Figure 2.8 with Figures 2.9 and 2.10, which show the same relationships for US Basic Oxygen Steel Plants, and French cement kilns, respectively. The general pattern is similar in all three cases. (More examples could have been produced from these industries.)

Thus EMIR is a model which bears a good relationship with reality at both the micro- and macro-levels. The assumptions about economies of scale take into account the considerable empirical research in these areas. The model of search for innovations is in accordance with the arguments presented and tested in Chapters 4 and 5; in particular the innovation procedure in EMIR is systemic and generated endogenously, it is subject to uncertainty, trial and error, and is partly appropriable, being relatively difficult to imitate. (This is in contrast to conventional models which take innovation as given, perfectly known and equally available to all actors.) The rules for generating and valuing plant construction decisions have been compared with reality in at least one industry and found to be adequate. The existence of plural interpretations of the world has also been incorporated into the model. In short, this is a genuinely dynamic and evolving economic model.

In the next Chapter the model is described in detail. In Chapters 9 and 10, experiments with the model are used to explore aspects of industry structure and technological development.

Chapter 8: Logical Description of EMIR Structure

In this chapter a detailed description and specification of the Evolutionary Model of Increasing Returns is given. A briefer and less technical outline of the model was provided in the previous chapter. In the two subsequent chapters, experiments with EMIR are described; for the most part, these should be intelligible without a detailed reading of this chapter.

1. BASIC ELEMENTS OF THE MODEL

1.1 Firms

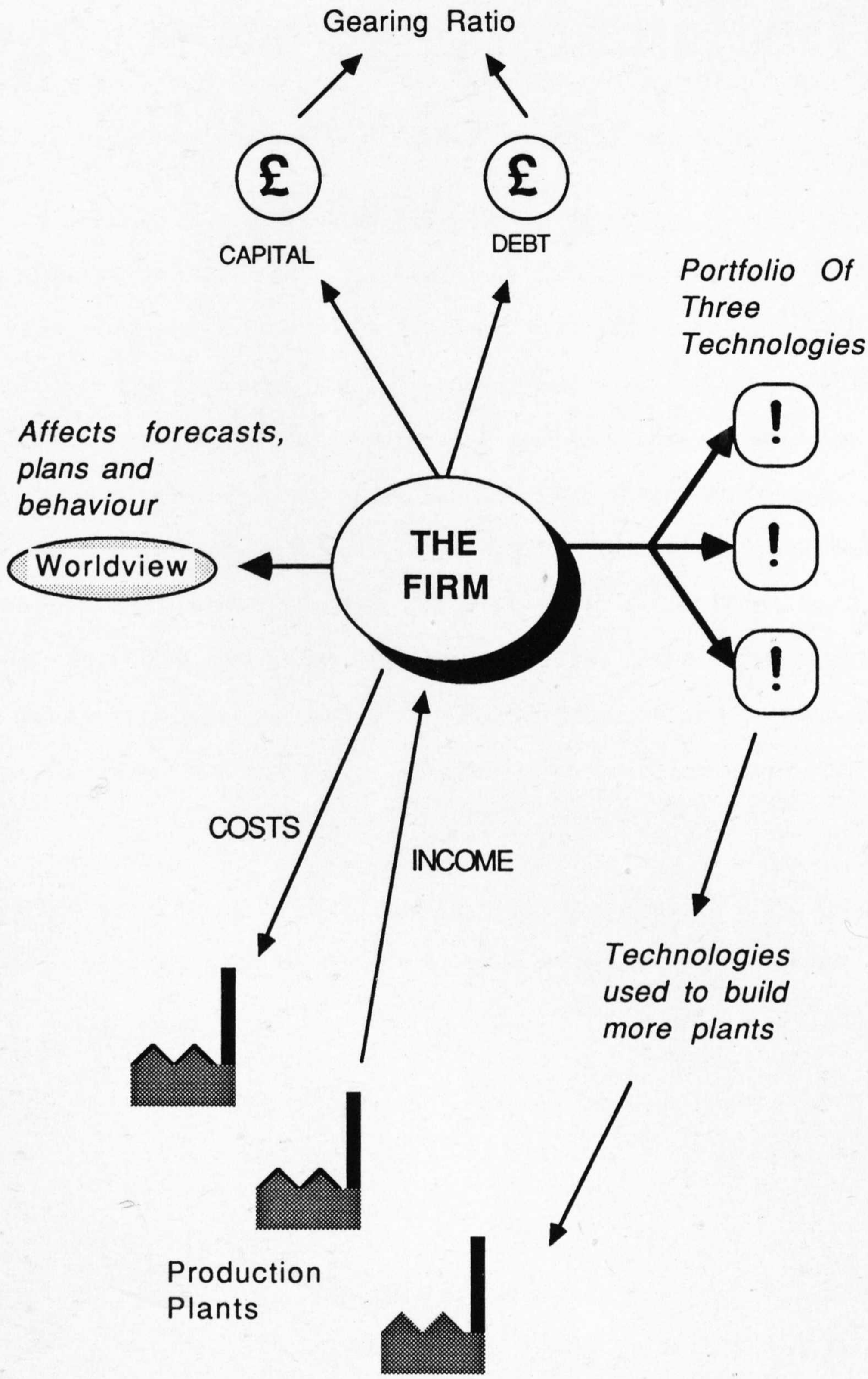
(See Fig. 1.1 on following page.)

The stylised actors (or decision-makers) in the simulated industry of EMIR are "firms". There are usually 4 to 16 firms in a simulation run. The firms operate production plants to generate income. They have to forecast future demand, and have the opportunity to build new plants to meet future demand. (Demand is exogenously specified.) Loss-making plants may be retired from use, and old plants are subject to a risk of failure (and hence scrapping).

Apart from its operation of production units, the firm is defined by three variables. The first of these is its Capital. This is set at 15,000 for all firms at the beginning of each run (arbitrary currency units). It is a measure of the assets of the firm. When a new plant is built by the firm, the capital construction cost of that plant is added to the firm's Capital; when a plant is retired or scrapped its capital cost is similarly deducted.

The second defining variable is the Debt of the firm. This is "money" borrowed by the firm to finance its operations. (The only costs which firms incur are those of building and operating plants - see below.)

Figure 1.1: Attributes of Firms in the Model



When a plant is built, the construction cost is added to its owner's Debt. (Retired plants are assumed to have zero scrap value, so Debt is not compensated when a plant leaves service.) Net profit (income less costs) is subtracted from Debt at the end of each period. Interest is charged on Debt. (See section 3.4 below for further details.)

The third defining element of the firm is its Worldview. The concept of the worldview was discussed extensively in Chapter 6. In EMIR the worldview concept is used to determine the firm's strategy, which is shaped by how the firm sees its business environment. Worldview affects the firm's forecasting of the future, its risk-averseness, its bias for or against capital-intensive projects, its innovation preferences, and its effective planning horizon. In the EMIR experiments discussed in this thesis only worldviews II (Sectist) and IV (Hierarchist) are employed. These two correspond to a conservative, and a more long-term, large scale strategy respectively. The worldviews are discussed in section 6.2 below, and are mentioned under other headings where they are relevant.

Firms also possess technological capabilities, which they seek to improve. A firm may hold three technologies at a time - see section 1.3.

1.2 Plants

A production plant is the physical embodiment of a particular technology (section 1.3) at a particular scale of operations. It is defined by the following:

Scale (size)	The maximum number of units of output every period. Plant scales typically vary from 40 to over 2000 in the runs to be described.

Capital (construction) cost This is the total cost to the owner of building the plant.

Labour (fixed) cost This is a cost which the owning firm has to bear for each period the plant is operated. It is an overhead cost, incurred regardless of the utilisation of the plant.

Variable cost The extra cost of manufacture. This is assumed to be things like raw materials, energy, and variable direct labour. It is only charged on that portion of the plant's capacity which is actually utilised.

"Capital intensity" will be referred to below and in following chapters; it is used in a loose (rather than strictly econometric) sense to mean the ratio of Capital (construction) costs of a plant compared with the other cost elements <u>per unit of theoretical maximum output</u>. If the maximum scale of output of a plant is X, then the capital intensity under this definition is:

$$\text{Capital cost} / [\text{Labour cost} + \text{Variable cost}] \qquad (1)$$

where Capital, Labour and Variable costs are as defined above.

Firms assess the perceived "average production cost" of a plant for ranking purposes (see below under "Decision Rules for Building New Plants" - section 5). This assessment depends upon the worldview of the firm, and is defined as:

$$\frac{1}{X} * [\text{Capital cost} * C(wv) + \text{Labour cost} * (1.1-C(wv)) + \text{Variable Cost}] \qquad (2)$$

where

$$C(wv) = 0.15 \quad (\text{worldview} = \text{II Sectist}) \qquad (3)$$
$$= 0.05 \quad (\text{worldview} = \text{IV Hierarchist})$$

Sectists place more weight upon capital costs, and Hierarchists upon Labour costs. Thus a IV-Hierarchist will perceive a high construction cost, low Labour cost plant as cheaper than will a II-Sectist. (See Chapter 6 for justification.)

Plants do not have an infinite lifetime. After ten years they have a 10% chance of failing and hence being scrapped in any given year. Their expected lifetime is thus twenty years. Discounted cashflow calculations of a plant's worth (Section 5 below) are therefore done over a twenty year horizon from completion date.

1.3 Technology

The nature of "a technology" has been explored in Chapter 4. In accordance with the approach used there, a technology in EMIR is seen as a potential "technique" for building a production plant within a particular scale range. It was argued in Chapter 4 that the assumption that all firms have full and equal access to all production technologies was false. In EMIR, a technology is modelled as the property of a specific firm (although it can be imitated by others once it has been used by its owner). Firms may hold up to three technologies in their "repertoire" at a time.

A technology in EMIR is defined by a quintuplet of variables (K, L, V, MAX, MIN):

K	= Capital cost coefficicent
L	= Labour " "
V	= Variable " "
MAX	= Maximum plant scale for which this technology is usable
MIN	= Minimum " " " " " " " "

A firm may choose to build a plant of scale X, which will have the following characteristics:

$$MIN = X = MAX \quad (4)$$

$$\text{Capital (construction) cost} = K * X^{0.7} \quad (5)$$

$$\text{Labour (fixed) cost} = L * X^{0.4} \quad (6)$$

$$\text{Variable cost} = V * X \quad (7)$$

There are therefore significant economies of scale with respect both to Capital (construction cost) and Labour (fixed overhead).

The cost-scale relationships defined in (5), (6) and (7) are typical of what Gold (1981) calls "capital-dominated" industries. For justification of the "0.7" and "0.4" rule coefficients, and of the scale-invariance of the variable cost component, see Tayler (1986) pp 21-31, and Chapter 2 herein, which give numerous references. See also Bruni (1963), Pratten (1971), and Haldi and Whitcomb (1967) for a wide range of industries; Norman (1979) for the cement industry; Lau and Tamura (1972) for petrochemicals; and Cockerill (1971) for brewing. Further discussion, and numerical examples, are given in Appendix 8H.

2. INNOVATION

All firms begin with the same technology. They have opportunities each time period to innovate i.e. locate a superior (K, L, V, MAX, MIN) quintuplet. There are three forms of innovation: incremental change, innovation by imitation, and scaleup innovation (which may be considered as another form of incremental innovation).

The principles expounded in Chapter 4 are used to model the innovation process:

(a) innovations are to some extent unpredictable in their outcomes, and the innovation process contains some random features;

(b) innovations are most likely to represent logical developments based on existing techniques, rather than dramatically new relationships;

(c) innovations are the "property" of the innovator, at least for a while;

(d) success in innovation is never guaranteed - it is essentially a "trial-and-error" process.

Chapter 4 argued that innovation strategies are conditioned by worldview (or, more prosaically, by general business strategies). The bias of innovations in the model is towards capital-saving (i.e. capital cost-reducing) changes for II-Sectists, and towards labour-saving changes for IV-Hierarchists. It is also assumed that the more cautious II-Sectists are more likely to be content to innovate by imitataion.

In the model, new technologies are generated by applying random changes to existing technologies (usually the firm's own, but sometimes others'). The innovating firm then decides whether to adopt the new technology as one of its 'repertoire' of three techniques.

The random factors are to some extent arbitrary; it would be very difficult to be sure exactly what they should be for any given industry, even were data available. A certain amount of trial and error has been used during the development of the model to find sensible rules which give steady but not too rapid technical progress. "Sensible" means that an innovation is likely to produce a cost saving of around 10%, but not of 50% or more. Similarly, a scaleup innovation could be a doubling of maximum plant size, but not a tenfold increase. These orders of magnitude seem more realistic compared with those observed for cost-reductions and scale increases in such industries as cement manufacture and bulk chemicals production. They also lead to simulations which are not too heavily-dependent upon chance events, as would be the case with more dramatic and rapid technological changes.

2.1 The Decision Process

The decision process is:

1. Imitation innovation will be attempted with probability (based on random number selection) as set out in the following table:

Worldview	Profitable	Unprofitable
	Probability of attempt	
II	0.3	0.5
IV	0.1	0.3

   In this context, "profitable" means "Average Rate of Return greater than 0". Rate of Return is defined below (equation (38)). Thus II's have a relative bias towards imitation, compared with IV's. Profitable firms are more likely to be satisfied with their existing techniques; unsuccessful firms are more likely to be willing to attempt to imitate successful competitors.

2. If no imitation innovation is selected, decide whether to attempt scaleup innovation. If the largest plant built so far (by any firm) is 20% or more of current demand, then no scaleup is attempted. Otherwise, let

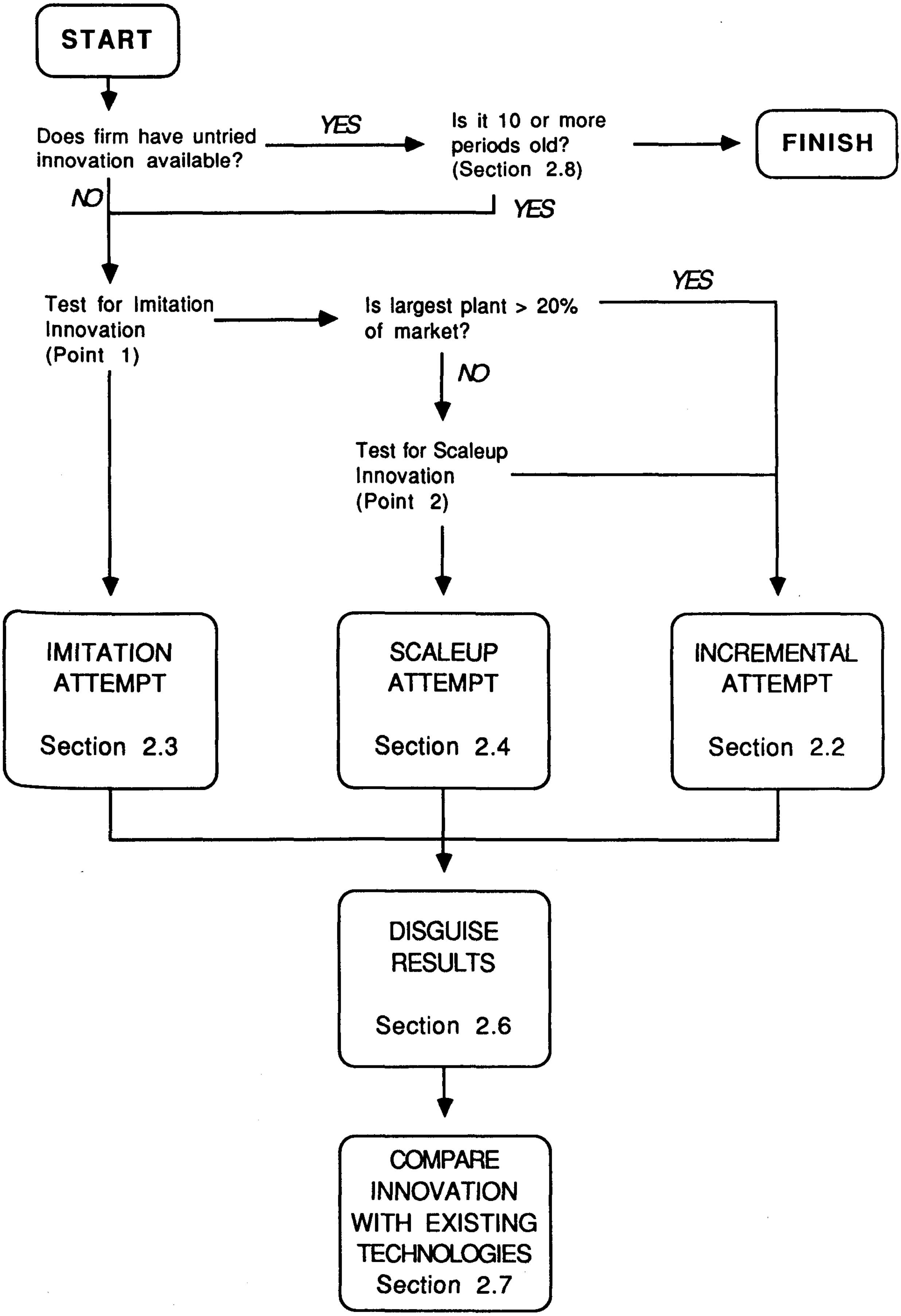
   M = Maximum of (No. plants operated by firm - 4, 0)

   Then the firm will attempt a scaleup innovation with the following probabilities:

Worldview	Probability
II	0.1 + M / 10
IV	0.4 + M / 10

   Thus a firm operating a large number of plants is more likely to

Fig 2.1: The Innovation Decision Process



investigate the possibility of rationalising output by constructing a larger plant. IV-Hierarchists are inherently more likely to attempt scaleup than II-Sectists, it was argued in Chapter 6.

3. If neither imitation nor scaleup innovation is attempted, then an incremental innovation will be tried. This last is the most likely and common form of innovation.

The innovation process for a firm is summarised in Fig 2.1.

2.2 Incremental Innovations

An incremental innovation is one which results in a small improvement in one or all of the technological cost parameters (K, L, V). Innovations are generated by deciding which of the firm's existing technologies is 'best', and then producing a candidate for innovation, as follows:

The 'best' existing technology is selected (see below). Let this technology be (K, L, V, MAX, MIN). Then an innovation is produced, identified as (K', L', V', MAX', MIN') by:

Let [X] be a random variable uniformly distributed between -x and +x, e.g. let [0.3] be a uniform distribution in the range [-0.3, 0.3].

IF worldview = II:

$$K' = K * (1 + [0.2])$$
$$L' = L * (1 + [0.2]) \qquad \text{with probability 0.4} \qquad (8)$$

$$K' = K * (1 + [0.05])$$
$$L' = L * (1 + [0.25]) \qquad \text{with probability 0.1} \qquad (9)$$

$$K' = K * (1 + [0.25])$$
$$L' = L * (1 + [0.05]) \qquad \text{with probability 0.5} \qquad (10)$$

$$V' = V * (1 + [0.025]) \qquad (11)$$

If worldview = IV:

$$K' = K * (1 + [0.2])$$
$$L' = L * (1 + [0.2]) \qquad \text{with probability } 0.6 \tag{12}$$

$$K' = K * (1 + [0.05])$$
$$L' = L * (1 + [0.25]) \qquad \text{with probability } 0.4 \tag{13}$$

$$V' = V * (1 + [0.025]) \tag{14}$$

2.3 Imitation Innovations

It is assumed that once a technology has been implemented it may be possible for others to imitate it. The knowledge that a particular way of doing things is both possible and successful may encourage others to try it out.

For an imitation innovation, the firm must first decide who to imitate. It does this by looking for the firm with the highest Rate of Return, measured by an exponentially-weighted moving average of (38). It then assesses which of this firm's technologies is the best (see section 2.7 - "Evaluation of Technologies", below), and copies this, subject to incremental changes. The technology imitated is (K, L, V, MAX, MIN), and the new technology is (K', L', V', MAX', MIN') generated by:

$$K' = K * (1 + [0.1]) \tag{15}$$
$$L' = L * (1 + [0.1]) \tag{16}$$
$$V' = V * (1 + [0.025]) \tag{17}$$
$$MAX' = MAX \tag{18}$$
$$MIN' = MIN \tag{20}$$

2.4 Scaleup Innovations

A scaleup innovation is one which seeks to remove bottlenecks or constraints to increasing scale, often with the objective of liberating further economies of scale. Scaleup innovations are discussed in detail in Chapter 4, Section 5. The main reference is Levin (1978); others are given in Chapter 4.

It is assumed that innovations of this kind not only raise the maximum scale of operations, but also (possibly) the minimum scale at which the technology is viable. A scaleup innovation attempt is simulated as follows (notation as above):

$$K' = K * (1 + [0.05]) \tag{21}$$

$$L' = L * (1 + [0.05]) \tag{22}$$

$$V' = V * (1 + [0.025]) \tag{23}$$

$$MAX' = MAX * (1.5 + [1.0]) \tag{24}$$

$$MIN' = MIN * (2.75 + [2.25]) \tag{25}$$

It is clearly possible to generate a scaleup innovation in which MIN' is bigger than MAX'. If this happens, the innovation is a failure, and it is rejected.

2.5 Radical Innovations

A radical innovation (which should be a rare event) involves a completely new set of parameters (K, L, V, MAX, MIN), which are not in any sense "near" the previous technology. Such innovations have been modelled with EMIR, but do not form any part of the experiments in the following chapters, so they will not be described further.

2.6 Uncertainty of Results

A key part of the argument of Chapter 4 was the element of uncertainty in the innovation process. This is obviously implicit in the random generation of incremental changes in equations (8) to (25). There is the additional issue of "learning by doing" - a distinction between the discovery of a design concept and its practical application. This is modelled by disguising the true parameters of an innovation by adding random factors, until the new technology is actually employed to construct a new plant. Thus the "evaluation of technologies" (section 2.7) is performed with a slightly distorted perception. It is possible both that inferior technologies may be accepted, and superior ones rejected.

New technologies are perceived by the innovators as follows:

$$K'' = K' * (1 + [0.1]) \tag{26}$$

$$L'' = L' * (1 + [0.1]) \tag{27}$$

$$V'' = V' * (1 + [0.025]) \tag{28}$$

$$MAX'' = MAX' * (1 + [0.1]) \tag{29}$$

$$MIN'' = MIN' * (1 + [0.1]) \tag{30}$$

2.7 Evaluation of Technologies

Firms are faced with the problem of evaluating the results of an innovation. They have to decide whether to keep an innovation, and possibly discard one of their existing three technologies. This may be an easy decision, but on the other hand one technology might be superior at one scale of production and inferior at different scales. They attempt to solve this problem by evaluating production costs at several different plant scales - five in all.

The possibilities are shown in Fig 2.2 (overpage).

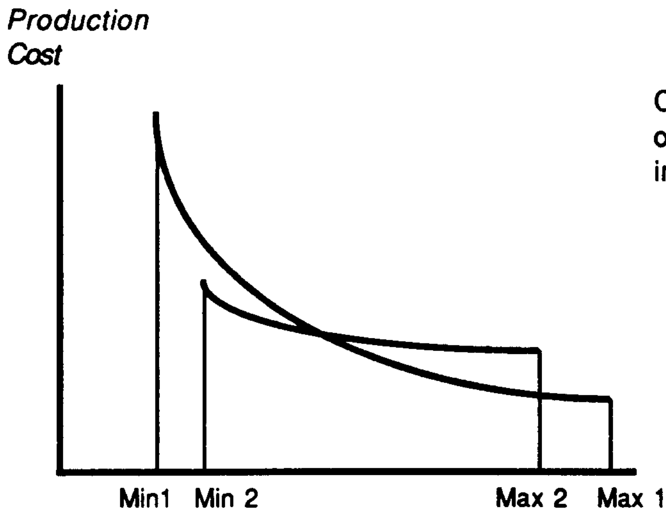
The algorithm for comparing two production technologies is to evaluate costs at the following five scales:

1) If their MIN value (minimum viable plant size) is the same:

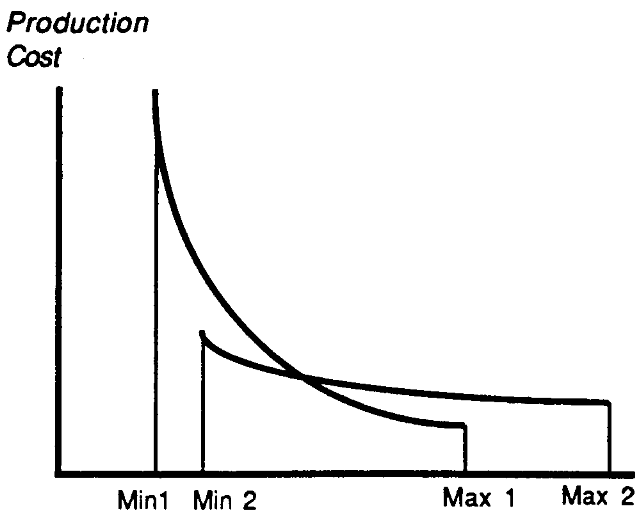
    Evaluate which has least production cost at MIN scale - award this technology one "point". "Production cost" is as defined above in equations (2) and (3), and depends upon the firm's worldview.

  Else

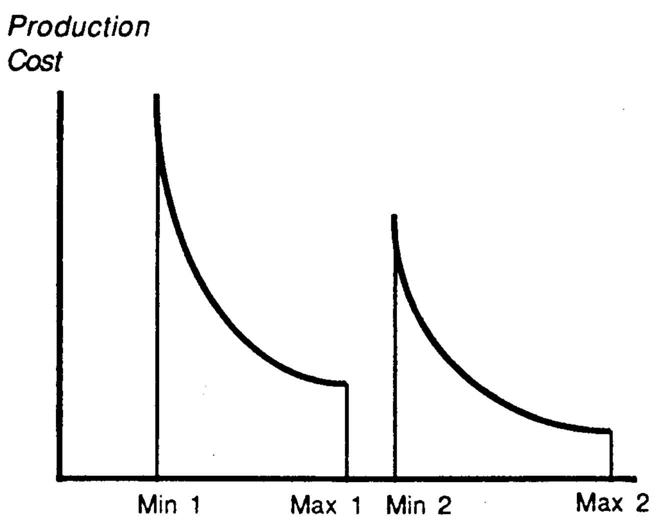
<u>**Figure 2.2: Evaluation of Technologies**</u>



Case A: One technology is viable over a range which wholly includes that of the other



Case B: The two technologies are viable over overlapping ranges



Case C: The viable ranges do not overlap

Small variations on these are possible, where MIN 1 = MIN 2, or MAX 1 = MAX 2 (Cases A and B), or MAX 1 = MIN 2 (Case C).

Technology with lowest MIN gains one "point"

2) If MAX values are the same:

   Award one point for least production cost at MAX scale

   Else

   Technology with higher MAX gains one point

3) Award one point for the least cost at the higher of the two MINs

4) Award one point for the least cost at the lower of the two MAXs

5) Award one point for the least cost at the plant scale which is the midpoint of the scales used in 4) and 5)

The technology with the highest score is the "winner". (Half a point is awarded for equal production costs.)

This means that necessary (but not always sufficient) conditions for a technology to be judged "better" are to either:

A) have lower production costs at the endpoints and midpoint of their common plant size range; or

B) be capable of building either larger or smaller plants than the other, or both, and to have lower costs at some point in their common range.

2.8 Rejection of Innovations

A firm may only have one untried technological combination in its repertoire at a time. (This is so that it cannot attempt to improve upon an innovation until it has actually tried it out, in accordance with the argument of chapter 4.) If an innovation remains unused and untried by a firm after ten periods, it is discarded. The reasons for this include:

(a) after a length of time the "technological frontier" will have moved on; the innovation will no longer represent best practice;

(b) it is assumed that "technology" is about the capability to produce things. That capabiility resides in knowledge and hence people, rather than things. Unused, the capability will decay;

(c) it is a simple assumption, which helps to keep the simulation flowing, without firms becoming "stuck" due to their inability to make technological improvements. After ten periods, the unsuccessful laggard will often have to try to catch up by imitation. (In practice in the model, not putting the innovation to use is often a sympton of failure to build new capacity. This is often both a cause and effect of poor performance.)

3. FINANCIAL ELEMENTS

3.1 Price-Setting

The demand for output from the plants which the firms operate is determined exogenously. It is assumed that demand is not affected by price, but rather that price is set in accordance with the relative proportions of supply (i.e. production capacity) and demand. Economic theory often assumes that (in the short run at least) demand is a function of price. Given that the intention of the model is to investigate different demand scenarios, this assumption is dropped.
Instead, price is set such that:

$$\text{Price} = \text{Average Production Cost} * (0.25 + \text{Utilisation}) \tag{31}$$

where

$$\text{Utilisation} = \text{Demand} / \text{Capacity} \tag{32}$$

$$\text{Average Production Cost} = \frac{\text{SUM(Production cost of plants)}}{\text{Total production capacity}} \tag{33}$$

$$\begin{aligned}\text{Production cost of a plant} = {} & 0.1 * \text{Capital construction cost} \\ & + \text{Labour Cost} \\ & + \text{Variable Cost at full capacity}\end{aligned} \tag{34}$$

This relationship implies that:

(i) prices fall in the long run if production costs fall; and

(ii) prices rise when demand rises in relation to supply, and fall when capacity exceeds supply by a significant margin.

There are a number of complex issues surrounding the pricing relationship. EMIR is not primarily a model of pricing strategy, and (31) suffices for our purposes here. A number of points about (31) to (34) are discussed in Appendix 8F.

(Note that the capital cost element is included in (34) for price-setting purposes only. The actual costs charged to the firm are the variable and fixed (labour) costs for the plants. The capital costs are accounted for by the extra Debt the firm has taken on.)

3.2 Allocation of Demand

If demand equals or exceeds available production capacity, then all plants are fully utilised.

If capacity exceeds demand, than all plants operate at the same utilisation, such that total demand is exactly met. See Appendix 8F on pricing for discussion of this assumption.

3.3 Gearing

EMIR is intended to be be an operational model, rather than one which faithfully recreates the balance-sheet and accounts of the firms simulated. It is, however, desirable to have some measures of commercial success and failure. It should not be possible for a firm which is consistently performing badly (having, for example, many plants with above-average production costs) to continue to build new capacity, especially if the new capacity is likely to embody poor technology. Firms with below-average production costs should conversely find it easier to order new plants.

In order to constrain investment decisions the concept of "Gearing" is introduced. This is defined as:

$$\text{Gearing} = \text{Debt} / \text{Capital} \tag{35}$$

where the firm's Debt and Capital are as described above in Section 1.2.

Firms are not allowed to make investments in further plant once their gearing has risen above a certain threshold. This threshold is set at:

Worldview	Maximum Gearing
II	0.5
IV	0.7

Acceptable "real-life" gearing levels vary between industries; however these values are not unrepresentative.

3.4 Interest and Dividends

Interest is charged on the period-end Debt at 5%. Since there is no inflation, this is a real interest rate. It is reasonably representative of recent history in the UK. Interest accrues on positive cash balances at 3% per period. Thus

$$\begin{aligned} \text{Interest} &= \text{Debt} * 0.05 \qquad \text{(Debt less than 0)} \\ &= \text{Debt} * 0.03 \qquad \text{(Debt greater than 0)} \end{aligned} \tag{36}$$

If the firm has paid off all borrowings (i.e. has negative Debt) then it pays dividends. Dividends paid are 40% of the trading profit (income less costs) and interest received, i.e.

$$\begin{aligned} \text{Dividend} &= 0 \qquad \text{if Debt is positive} \\ &= 0.4 * (\text{Income} - \text{Costs} + \text{Interest Received}) \quad \text{else} \end{aligned} \tag{37}$$

A 40% dividend payout is equivalent to 2.5 times dividend cover, which is considered commercially safe in many industries.

Again, the assumption that dividends are not paid unless Debt is fully repaid is unrealistically generous to the firms. However, it is employed to make sure that financial factors do not dominate operational performance in the model.

3.5 Bankruptcy

If a firm has:

(a) no plants in operation; and

(b) gearing of 80% or more;

then it is declared Bankrupt, and is removed from the simulation. (It is not replaced.) If (a) and (b) are both true, then the firm is paying interest and receiving no income, and its gearing means that it will never be able to build another plant to obtain income.

3.6 Rate of Return

Rate of return is used to assess who is doing best when firms are seeking to innovate by imitation. It is calculated as:

$$\text{Rate of Return \%} = 100 * \frac{(\text{Income} - \text{Costs} - \text{Interest})}{\text{Capital} + \text{Debt}} \qquad (38)$$

i.e. it is the net return this period on the total funds used in the business. (38) defines the Rate of Return for a single period; for choosing the "imitatee" an exponential moving average is used (coefficient 0.5), which reduces the effect of "fluke" single-period results.

4. DEMAND AND CAPACITY

4.1 Forecasting

Firms in EMIR are faced with uncertain future demand, which they are obliged to forecast. Forecasts are biased towards long-term or short-term data, according to whether firms are IV's or II's (see section 6.2 below for full summary). To forecast future demand the firms use Holt's Method of exponentially-weighted moving averages. Let:

m(t) = current estimate of level of demand

b(t) = current estimate of rate of growth of demand

y(t) = actual demand at time t

Y(t) = forecast of demand at time t made at time t-1

Then:

$$e(t) = y(t) - Y(t) \tag{39}$$

$$m(t) = m(t-1) + b(t-1) + A1 * e(t) \tag{40}$$

$$b(t) = b(t-1) + A2 * e(t) \tag{41}$$

The forecast for k time periods ahead, made at time t, is given by:

$$Y(t,k) = m(t) + k * b(t) \tag{42}$$

The parameters A1 and A2 affect the weightings given to past data. They depend upon the worldview of the forecasting firm, and the values used are:

Worldview	A1	A2
II	0.4	0.15
IV	0.2	0.08

I have tested these values for reasonableness in other forecasting applications. The implication of the values chosen is that II's take less account of past history than IV's, which latter tend to take a longer-term perspective to decision-making. (See also "J. Royal Statistical Society" 1975, p.205.) Some sample forecasts are given in Appendix 8I.

4.2 Random Failures

Production plants do not have an infinite life. In this model they are assumed to have ten periods of trouble-free operation, and then to be subject to a risk of catastrophic failure. In each period after the first ten, each plant has a 10% probability of "failing". It is then retired immediately, with no scrap value to its owner.

The 10% probability of failure implies an average life of 20 periods for a plant (10 risk-free, and an average of 10 more before random failure).

4.3 Retiring Loss-Makers

If a plant is unprofitable and is losing money for its owner, consideration must be given to closing it down. If a plant was loss-making (i.e. income was less than total costs) in the previous period it is a candidate for closure if either

(a) total industry capacity was greater than demand last period, or

(b) this plant's production cost was more than 1.5 times the industry price last period.

If either of these hold, then the expected financial performance over the next two periods is calculated. Forecast demand and capacity are used to get expected sales; last period's price is used, together with the known costs of the plant, to determine the expected profit or loss. The performance for each period is discounted back at the appropriate rate. (See next section for details - the aproach is exactly as for new builds, but only the next two periods are considered.) If the result is negative the plant is retired, unless the firm owns more then one loss-maker, in which case the plant with the largest expected loss per unit of output is retired. Only one plant per firm per period is retired on loss-making grounds, to share the "pain" between firms when the model industry is in times of serious overcapacity.

5. DECISION RULE FOR BUILDING NEW PLANTS

The approach to capacity addition and technology selection used in EMIR has been developed by applying "common-sense" decision rules. The algorithm described in this section is set out from the viewpoint of an individual decision-maker operating under uncertainty.

"Common sense" in this context means an application of basic investment appraisal techniques. A similar approach was developed by Buzacott (1980), who derived a good description of process choice and plant scale decisions in the Canadian steel industry over several decades. The EMIR model is related in spirit (though not in detail) to mathematical descriptions used by Ghemawat (1984) and by Dosi (1984, ch 3). It owes its conceptual foundations (and this applies to all aspects of EMIR) to O.R. and Decision Theory, rather than to traditional economic tools of analysis.

5.1 Net Present Values

The decision process for new capacity relies upon a Net Present Value (NPV) approach. This is generally considered superior to other approaches to investment appraisal (both discounted cashflow and others), particularly where there is more than one possible project. (See Weston and Brigham (1979), Rappaport (1986).)

The idea behind the NPV is that cashflows in the future should be given less weight than current cashflows. To achieve this, future cashflows are adjusted by a discount factor (which increases the further in the future they occur). A standard introduction to the NPV method is Brealey and Myers (1988).

Frequently, a project will have a large negative cashflow (i.e. an investment) in the first year, and a series of positive cashflows (returns on the investment) for several years afterwards. This is essentially the case with plant construction decisions in EMIR. To obtain the NPV of the project, the future cashflows must be discounted by the appropriate factors. All cashflows, positive and negative, are summed to find the NPV of the project. If this is positive, then the investment is considered worthwhile at that particular discount rate.

5.2 Discount Factors

There is a considerable literature on the selection of appropriate discount rates for investment decisions. Leaving aside academic considerations, a wide range of discount rates is employed in practice, depending upon the industry, cost of capital and risk-averseness of the decision-makers. In the model this diversity is reflected by using different discount rates for the worldviews.

The IV-Hierarchists have a more long-term attitude, and are less risk-averse than the II's. A discount rate of 6% is used for assessing investments for IV's, and 9% for the more cautious and short-term II's.

The discount rate r is applied to generate the discount factor after k years of $1 / (1 + r)^k$. As an indication of the relative effects of the discount factors, the value of £1000 after various periods is shown below:

Rate	6%	9%
After 0 years	1000	1000
" 5 "	747	650
" 10 "	558	422
" 15 "	417	275
" 20 "	311	178

As noted above, the expected life of plants is 20 years; all projections therefore use a 20-year life, although in practice the actual life of the plant might be as low as 11 years, or as high as 40 years. (There is about a 5% chance of a plant surviving this long.)

5.3 Capacity - Demand Gap

The simulated firms use their knowledge of present capacity (plus planned future additions next period of plants they and their competitors have under construction), and their forecast of future demand (see Section 4.1 above), to decide whether there is scope for building a new plant.

Firms forecast the expected gap between capacity and demand 2, 3, 4, and 5 periods in the future. (Plant construction lead-time is assumed to be 2 periods, so there is no point in considering the gap 1 period ahead.) Additionally, because plants can still operate profitably at less than 100% utilisation, an overcapacity margin is allowed. For the aggressive IV's this margin is 15%, and for the II's it is 5%.

Define the forecast demand gap k periods ahead, forecast at time t, as

$$G(t,k) = Y(t,k) * D(wv) - \text{Capacity}(t,k) \tag{43}$$

where

Y(t,k) is the demand forecast from equation (42)

Capacity(t,k) is existing capacity plus plants ordered by all firms

D(wv) = 1.05 (worldview = II Sectist)

= 1.15 (worldview = IV Hierarchist)

The firm calculates the size of the gap, including planned overcapacity, and considers the effects of constructing a plant of this output (i.e of sizes G(t,2), ... , G(t,5)). The plant might be built with any one of three technologies, so there are potentially 3 times 4 (different gaps) = 12 plant projects to be considered. Construction costs, operating costs and expected revenues are used to assess the NPV of each construction project. Revenues for new plants are calculated on the basis of a maximum utilisation of 90%, on the assumption that other plants would be built if the industry had very high utilisation levels in the future. That is, income is based on the minimum of the forecast gap and 90% utilisation for each of the following 20 periods. Thus the income forecast at time t for k periods ahead for building a plant of size G(t,j) is

$$I(t,k) = PRICE * MIN\ (G(t,k),\ 0.9 * G(t,j)) \qquad (44)$$

where PRICE is the market price.

The price used in calculating investment decisions is the same as the current price. That is, it is assumed that the best estimate of the market price of output in all future periods is the price in the period in which the decision is being taken. This has the effect of making firms more likely to choose to build plants in periods of high utilisation, and less likely to build when capacity is under-utilised.

If the fixed (i.e. Labour) production costs of the plant are L, and the variable costs are V per unit of output, then the profit (loss) P(t,k) forecast at time t for k periods ahead is given by

$$P(t,k) = I(t,k) - L - V * MIN\ (G(t,k),\ 0.9 * G(t,j) \qquad (45)$$

Then if the discount factor is denoted by r, the NPV of the project, evaluated at time t, is given by:

$$NPV(t) = \sum_{k=1}^{22} (P(t,k) - K(t,k)) / (1 + r)^k \qquad (46)$$

where

$$K(t,1) = K(t,2) = \text{half the capital construction cost}$$

$$K(t,k) = 0 \text{ (k greater than 2)}$$

and

$$P(t,1) = P(t,2) = 0 \text{ (because the plant is not finished for two periods)}$$

5.4 Rationalising Existing Capacity

Besides building to meet future expected shortfalls, firms may build new large plants to replace older ones. They might wish to do this either because a better technology had become available to them, or because they had the opportunity to replace several small and uneconomic plants with a single large-scale plant, or both.

The procedure is similar to that followed above, except that the demand gap (plus allowable overcapacity) is estimated on the assumption that existing plants owned by the firm are to be retired. Building plants of this new "gap" size is assessed in the same way as above. The difference is that the NPV of the new plants is compared with that of the plant(s) which are candidates to be retired. A project must show an NPV larger than that of the plants to be retired (on which, of course, the capital cost is entirely sunk) for the new plant to be ordered.

The rules for "rationalisation" building are as follows:

A) Existing plants are ranked by their average production costs, defined as in (2). It is assumed that the firm will try to replace old plants with the highest production costs first, so this provides an ordering for the decision.

B) Let the capacities of the existing plants be C(1), C(2), ..., C(n), where the n plants are in decreasing order of production cost. Then define the future demand gap k periods ahead after j plants have been retired by

$$G(t,k,j) = G(t,k) + \sum_{i=1}^{j} C(i) \qquad (47)$$

C) The "marginal" NPV of each existing plant is calculated in turn by applying (44), (45) and (46) with G(t,k,j-1) replacing G(t,k), and P(t,k,j-1) replacing P(t,k). That is, the NPV of the jth plant is forecasted under the condition that the j-1 plants with a higher production cost have been retired first, so allowing the plant a higher level of sales than it might have otherwise achieved.

Since the existing plants need no further capital expenditure, the NPV of the jth plant on retiring the j-1 higher-cost plants is

$$PV(j) = \sum_{k=1}^{22} P(t,k,j-1) \ / \ (1+r)^k \tag{48}$$

D) The NPV of the proposed new plant of size G(t,k,j) is assessed similarly to (46). Thus the NPV on retiring j plants is given by

$$NPV(t,j) = \sum_{k=1}^{22} (P(t,k,j-1) - K(t,k)) \ / \ (1+r)^k \tag{49}$$

An additional criterion for accepting a proposal to build a plant is that its NPV must exceed the sum of the NPVs of the existing plants it replaces, derived as in (48). Thus

$$NPV(t,j) \ \text{ greater than } \ \sum_{m=1}^{j} PV(m) \tag{50}$$

Some comments on this condition, and other issues arising from section 5.4, are made in Appendix 8G.

Ordering a plant based on a proposal for rationalisation does not commit the builder to retire the old plants; that decision is taken in the light of later conditions (demand, capacity and price) in the market, in exactly the same way as the decision to retire (or not) any other plant.

5.5 Ordering and Building Plants

If one or more projects can be found with positive net present value, then that with largest NPV is ordered. Only one new plant may be constructed per firm per time period.

The construction cost of the plant is derived from the scale of output and technological quintuplet employed. It is charged equally over the next two periods. The plant then begins to operate.

The construction decision is assumed to be immediately known to all competitors. This means that all subsequent capacity decisions take the future addition into account. The justification for this is that firms in heavy industries such as steel production, petrochemicals, etc frequently engage in "pre-emptive" capacity announcements. The ordering of significant extra production capacity in such industries is generally given considerable publicity, with the deliberate intention of dissuading competitors from expanding their own capacity. See also Ghemawat (1984) for both a theoretical model and empirical analysis of the capacity expansion process in the US Titanium Dioxide industry, where the role of "pre-emptive" capacity announcements is discussed.

Firms take decisions in randomised order each period. In times of industry growth there is an advantage in taking the first decision, since it is likely to allow the firm to construct new capacity. In difficult times the first decision is often disadvantageous, since it will force the firm to retire a plant, thus easing the situation for its competitors.

An alternative would have been to allow firms knowledge only of existing capacity. In this case they would only adjust their forecasts of future industry capacity at the time a new plant became operational, rather than two periods earlier when it was ordered. The main arguments for doing this could be that

(a) it is a more realistic description of actual behaviour, and

(b) it would produce more realistic overcapacity situations in the model, as many firms sought to fill the same demand gap.

The objection to (a) is that there is evidence (quoted above) that in some (or possibly many) cases future capacity intentions are deliberately announced by firms in order to engineer a "bloodless" pre-emption. The objections to (b) are that overcapacity is frequently present anyway, due to the capacity - price relationship (see chapter 7 for a description of the phenomenon), and that when it was tried it gave pathological results. For example, it commonly happens that plants of scale at least 10% of the total industry demand are constructed. These plants eventually fail. In the likely case where each of 16 competing firms then builds a plant to fill this gap, their behaviour will lead to 150% overcapacity within two periods (other things being equal). This gross level of overcapacity is less realistic than the behaviour exhibited in the model at present.

6. SUMMARY ON BOUNDED RATIONALITY

In conclusion, two important "themes" in the structure of the model - uncertainty, and worldviews - are summarised. The existence of uncertainty, and the presence of cognitive biases, means that the model contains a fairly sophisticated formulation of bounded rationality.

6.1 Uncertainty

By way of reminder, uncertainty plays a part in two key areas of the model:

Firstly, the future demand is unknown and has to be forecast by the firms.

Secondly, innovation is an uncertain process. Innovations are generated randomly; the outcome of an attempted technological change is never assured. Furthermore, the properties of an innovation are not fully known until it has been implemented in a real plant.

6.2 Worldview

In this model two of the worldviews discussed in Chapter 6 have been used. They are the Hierarchist (IV) worldview, and the Sectist (II) worldview. These two were selected because they have identifiable biases for and against large scale technology.

In summary, the IV-Hierarchist worldview was characterised by: a longer-term, optimising approach to planning, and a tendency to favour large-scale, capital-intensive technologies.

The II-Sectist worldview was in contrast based on: a cautious, shorter-term and more risk-averse approach to planning and a tendency in favour of smaller-scale, less capital-intensive technology.

These differences are operationalised in the model under the following headings:

Forecasting: The IV's use parameters in the forecasting module which mean that they take account of longer-term trends in the demand time series. (See equations (39) to (42).)

Discount Rate: The IV's use a lower discount rate for assessing plant construction projects. This means that they place relatively less weight on the short-term payoffs, and relatively more weight on the long-term returns, from their capacity decisions.

Overcapacity: II's cautiously plan for a lower level of overcapacity in the industry (equation (43)).

Gearing and Financial Risk: The IV's are willing to accept higher gearing levels than the more cautious II's.

Capital Intensity: The worldviews evaluate average costs in different ways (see equations (2) and (3) above). The IV's weight capital costs less heavily than II's, leading them to tend to adopt more capital-intensive technologies.

Innovation Search: The IV's are more likely to attempt Labour-saving incremental innovations then are II's (equations (8) to (14)). They are less likely to take the conservative route of imitating others' successful innovations, and more likely to attempt to scaleup (see section 2.1).

7. TECHNICAL ISSUES

7.1 Starting Values

The simulation begins with a given number of firms (usually either 4 or 16 in the experiments to be described). The simulation can be begun with each firm in an entirely arbitrary state - i.e. with any given Capital, Debt, Worldview, set of three technological options, and any number of plants, each built using a (possibly) different technology.

For reasons of comparison, however, it was important to begin each simulation with the same starting conditions. It was also important to start with each firm in the same position as its competitors, so that the asymmetries which develop between firms during the simulation could be explained in terms of the effects of the simulation variables.

Some preliminary experimentation was done to find appropriate opening conditions. For the runs to be described in the following chapter, an opening Capital value of 15,000 was used. To this would be added the value of the initial plant(s), which would be financed by Debt. This generally produced opening Capital of 17,000 to 18,000, with Debt of 2,000 to 3,000.

Thus opening Gearing is low, perhaps unrealistically so. The reason for this is that EMIR is not primarily a financial model. Giving firms high opening gearing makes the role of that constraint very important. The intention is only to ensure that firms are not permitted to continue to operate indefinitely when they are performing poorly. The model is about competition through technology and scale choice, not through financial performance ratios.

Depending upon the number of firms in the industry, all initial plants are of size 80 units output per period (for 4-firm industries) or 40 units output (16-firm industries). The number of plants per firm depends upon the demand series simulated.

All firms and plants start the simulation with the same production technology. This only varies between high and low capital intensity runs.

For more details on initial conditions for the simulation experiments, see the opening sections of the next chapter, and Appendix 9A.

7.2 Implementation

EMIR is written in BASIC, and runs on an Apricot PC. A full listing of the program code is given in Appendix 8A.

A full run of the model, using 16 firms and running for 60 simulated periods, takes several hours. This could of course be significantly improved by transferring to a more modern machine.

Each simulation run is controlled from a data file which specifies the demand series, number of firms, initial plants and technologies, and other information.

The output from a model run consists of two data files which store details for each period of the simulation. One records the state of each firm in each period, and the capacity and price for the industry as a whole. The second stores details of all plants constructed.

There is also screen output from the program for each period, and while firms are analysing their options. This allows the operator to halt the program to investigate the state of the model at any time. (See also below.)

7.3 Technical Appendices

There are technical appendices which accompany the program listing. They are as follows:

Appendix 8B **Arrays used in EMIR version 3.2.** This lists and describes all array variables used in the program listing.

Appendix 8C **EMIR Program Logical Structure.** This gives a structured English high-level "pseudocode" version of the program. It is commented with labels which are also placed as comments in the program listing.

Appendix 8D **EMIR Previous Versions.** This lists the main development stages of the model, showing how functionality was developed step-by-step to assist in validation and testing of the program.

Appendix 8E **Debug Output.** This lists, with a brief description, the lines of the program which send output to the PC screen and act as testing aids in validating the simulation results.

Chapter 9: Experimental Results with EMIR

> "... it is evident that the co-existence of increasing returns and competition ... is a very prominent feature of de-centralised economic systems but the manner of functioning of which is still a largely uncharted territory for the economist."
>
> Kaldor (1972)

1. INTRODUCTION

The EMIR model was described in the preceding chapter. In this chapter some preliminary results with EMIR are outlined to show the scope of this model, and the kinds of new results which are possible.

Section 2 below describes the basic set of runs done with the model. Certain conclusions are produced from these runs. In sections 3, 4 and 5 these results are investigated further, highlighting particularly the importance of gaining market share for competitive success under increasing returns (i.e. where there are economies of scale and the possibility of technological innovations).

The experiments examine the influence of a number of factors on the outcome of 60-period simulation runs. Outcomes are assessed in terms of resultant industry concentration, plants scales, production cost levels, and cumulative technological progress. The influencing factors are such things as the strategies (worldviews) of the firms, the growth in market demand, the number of firms in the industry, and the characteristics of the initial production technology. The latter is particularly important, for it is often asserted that plants have to be built big because of the requirements of the production processes involved.

2. THE INITIAL EXPERIMENTS

The approach was to run the model whilst varying six factors which were expected to affect the outcome of the simulations. Five of these related to the starting conditions of the firms in the simulated industry: the presence (or absence) of technical change in the simulation; the numbers of firms in the simulated industry; the initial capital intensity of the production process; the initial maximum scale of the production plants in the industry; and the worldview (strategy) of the firms. Each of these five experimental factors could take one of two values. The sixth experimental variation was to alter the demand profile faced by the industry; three different demand scenarios were used in all.

Experimental design is described in section 2.1. In sections 2.2 and 2.3 the form of the results, and the method of analysis used, are given. Sections 2.4 and 2.5 present the simulation results. Regression analysis is used in section 2.6 to verify the significance of the predictors of industry structure found in 2.4 and 2.5; these are summarised again in section 2.7.

2.1 Experimental Design

The initial objective was to establish the essentials of how the model behaves. The ultimate objective was to gain insight into the determinants of industry structure and of firm and plant scale. The method used was to study the effects of changing six important variables in the simulated industry:

1. Number of Firms in the industry. This was set at either 4 or 16, to represent a tightly oligopolistic situation and a more fluid competitive scenario.

2. Capital Intensity of the production process was set at either "High" or "Low" at the begining of the simulation. This was represented by a doubling of the capital coefficient in the initial technology given to all firms at the beginning of the run. (See Chapter 8, section 1.2.) A more capital-intensive process might be expected to make economies of scale more significant for

competitive success, leading to a greater degree of concentration and larger plant sizes. (See also Appendix 9A.)

3. Technical Change was either allowed or barred. (Innovations which allow an increase in maximum plant scale count as technical change.) This means that the effects of economies of scale alone can be separated from those of the other form of increasing returns, technological learning.

4. Maximum Plant Scale at the beginning was set at either 100 or 400. (This was therefore the permanent ceiling in the "No Technical Change" runs.) The object was to see whether industry structure is heavily determined by the availability of substantial scale economies, or relatively insensitive to them. An additional objective was to investigate the factors leading to giant plant sizes; if eventual unit scale were found to be independent of initial technological maxima then it could be concluded that scale in the simulated industry was not "technology-driven".

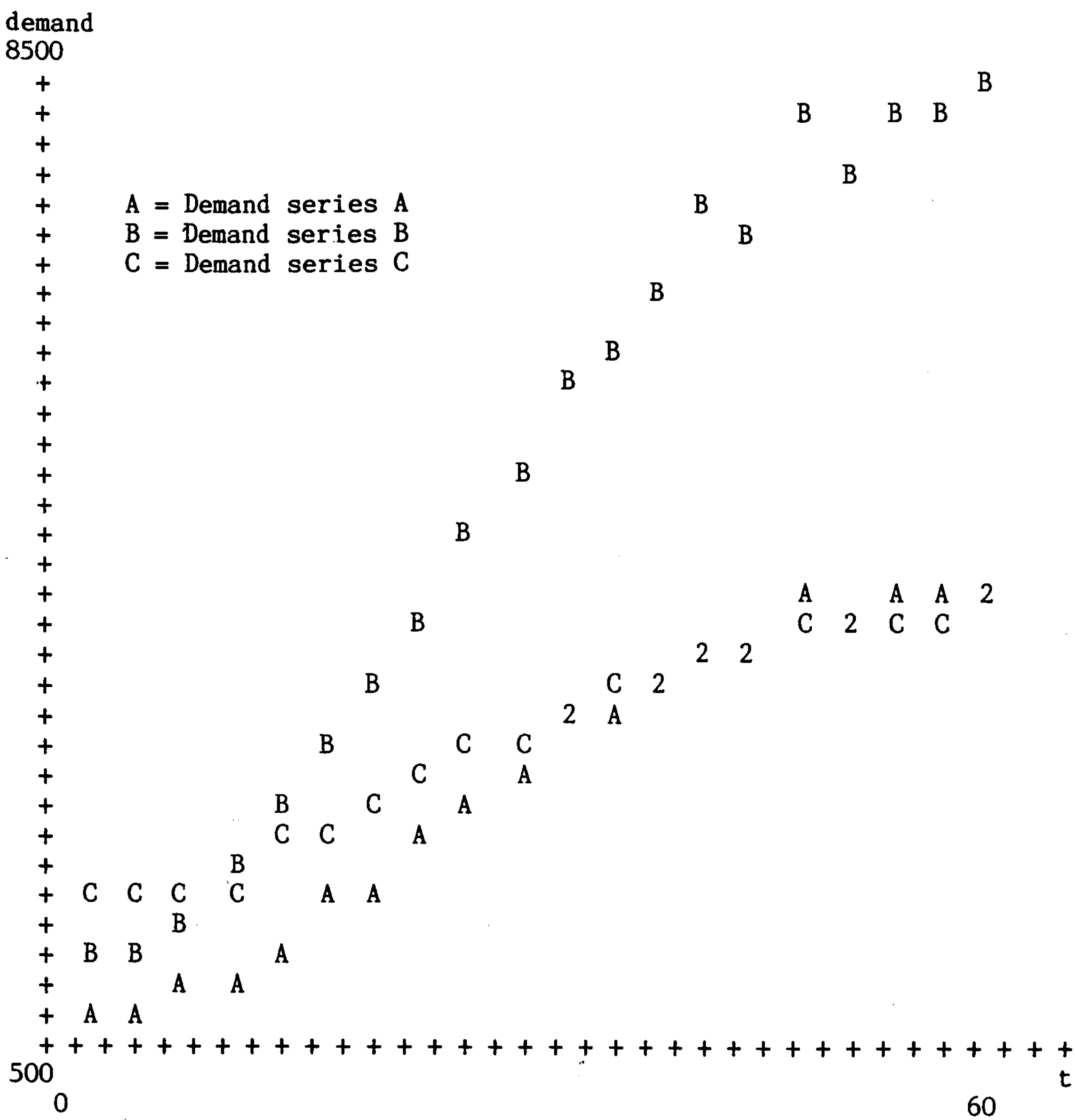
5. Worldview of all the firms was either II or IV in each run. (Sectist or Hierarchist respectively - see Chapter 6.) All firms in each run had the same worldview. IV's are expected to have a larger-scale and more aggressive orientation compared with the more cautious II's. The object was to see to what extent the "pure" strategies influence outcome; does a more agressive and long-term view on the part of the actors change the resulting industry structure?

6. Demand Series. Three demand series were used, designated A, B and C - see Figure 2.1. Demand is the key exogenous input to the model. As such, it is useful to compare influences due to other

experimental variables between demand scenarios. It might also be the case that plant scales (for example) are affected by the size of the available market. Each demand series runs for 60 simulated periods.

Demand series A and B are similar, but B has twice the rate of growth. C starts at a higher level than either, but grows more slowly. By using this combination, it is hoped to factor out any results which are purely the consequences of quirks in the experimental demand scenario.

<u>Figure 2.1: Demand Series for Simulations</u>



Each experimental run is identified in the results by a code e.g. 4H1IVA. This code is constructed as follows:

4 / 16	Depending on whether 4 or 16 firms used
H / L	High or Low capital intensity
1 / 4	Initial plant scale maximum 100 or 400
II/IV	Firm worldviews II or IV
A/B/C	Demand series A, B or C
N	In place of A/B/C if technical change is barred. ("No technical change" runs were done with demand series A only.)

Thus 4H1IVA denotes a run with 4 firms, High capital intensity, initial maximum plant scale of 100, all firms having worldview IV, and using demand series A. The absence of the "N" at the end shows that this run was done with technical change allowed.

Each experiment was performed four times, with the random number initialiser taking the values 1, 2, 3, 4 successively. (The order of firms taking capacity decisions, "old-age" plant failures, and technical innovations are determined by random numbers.) All possible combinations of experimental variables were tried, apart from restricting "No Technical Change" to demand series A only. This produced a total set of 256 simulation runs. Earlier experiments had indicated the kinds of variability of results which were likely to be encountered; 256 runs appeared to be ample to prove statistical significance for results using only simple non-parametric tests.

The demand series, and the starting conditions for the simulations (including technology variations for Low/High capital intensity), are listed in Appendix 9A.

2.2 Results of Basic Runs

The output from these 256 simulation runs consists of time-series data files on floppy diskettes. A brief summary is difficult; the data files take about about 8 Mb of storage space. The bulk of the results have been placed in the Appendices. The rest of this Chapter is essentially a summary of the detailed comparisons set out in Appendices 9D to 9K.

Appendix 9B gives the results of all of the runs in tabular form. Key outcome variables, representing industry structure, technology, plant size and costs, are recorded at the end of each simulation.

The methodology for analysing the results is set out in section 2.3.

2.3 Method of Analysis

The effects of each experimental factor are assessed by pairing up simulation runs. The pairings are arranged such that only the single factor under scrutiny differs between the runs. For example, suppose the factor for analysis were worldview. The run 4H1IVA.1 would be paired with 4H1IIA.1 (the ".1" denoting that the run was performed with random number seed = 1), 16L4IVB.2 with 16L4IIB.2, 16H1IVC.3 with 16H1IIC.3, etc. For a full analysis over all three demand series and four random number streams, the "technical change" runs allow a total of 96 comparisons for each factor, whilst the "no technical change" runs permit 32 comparisons to be made.

Having made the pairings, it is then possible to perform simple non-parametric statistical tests on the results to assess the significance of the experimental variables. For example, for comparing average plant scale at the end of the simulations, the sign of the difference (+ or -) between plant sizes at t=59 would be calculated for the 96 pairings. (Cases where the differences are zero are discarded.) The 96 + or - differences can then be tested against the hypothesis that there is no difference between average plant scale for runs with worldview IV and worldview II (for example). The null hypothesis is that there are equal numbers of + and - differences; this is tested by using the Normal approximation to the Binomial distribution. See Appendix 9D for more details.

Clearly, a more sophisticated statistical analysis of variance could be performed with the data. However, as will be seen, this was not needed to establish considerable statistical confidence in the results.

The output measures (all taken at period t=59) used for comparison purposes are set out in Appendix 9B. They can be summarised under the following headings:

A) **Production Costs** - average production costs, production costs of the most efficient firm, and market price.

B) **Industry Concentration** - the proportion of firms still operating plants at the end of the simulation, and the proportion of industry capacity operated by the top quarter and top half of the firms.

C) **Mortality** - the proportion of bankrupt firms and, to a lesser extent, the proportion of firms not operating any plants. (Normally only one of the two is significant.)

D) **Plant Sizes** - average plant scale, and the size of the biggest plant built.

E) **Technological Progress** - the average and best (i.e. lowest) technological coefficients for K (capital construction cost) and L (fixed labour cost). Clearly there can be different biases for and against K and L within this grouping.

In some of these cases, both average values and "best " or "biggest" are referred to. In the analyses which follow, average values were given greater weight in assessing outcomes.

2.4 Analysis - Runs with No Technical Change

As stated above, a set of 64 simulation runs was performed in which technical change was barred; firms were unable to improve upon the production technique with which they were endowed at the beginning of each run (see Appendix 9A for details). The results described in this section, therefore, demonstrate purely the consequences of competitive interactions between firms in which the only source of increasing returns is the potential to gain scale economies by building plants up to size 100 or 400 (depending upon simulation scenario).

The detailed results from these runs are given in Appendix 9B. The statistical analysis, based upon pairings keeping all but one experimental variable constant as described in section 2.3 above, is given in Appendix 9D.

Table 2.4.1: Summary of Influence of Starting Configurations on Key Industry Performance Measures - No Technical Change Runs (Demand Series A only)

	Influence (alternative)			
Performance Measure:	Worldview IV (II)	16 Firms (4 firms)	Plant Size 400 (size 100)	High Capital Intensity (Low)
Production Costs	---	+++	---	+++
Industry Concentration	+	+++	+++	-
Mortality	+++	+++	+++	+
Plant Sizes (Average)	+++	---	+++	.

KEY: +++ (---) positive (negative) influence, significant at 0.1% level
+ (-) positive (negative) influence, significant at 5% level
. no statistically significant influence either way

The influences on summary output measures are reported in Table 2.4.1.

The absence of technical change in these runs means that there are no differences in technological progress, maximum plant scale or lowest achievable production costs.

Table 2.4.1 shows that, for example, starting a simulation run with 16 firms (instead of 4 firms) has a positive effect upon production costs (i.e. they are higher), and a negative effect upon plant sizes (they are lower). It has a positive effect upon industry concentration (concentration becomes greater), and upon firms' mortality (more firms are either Bankrupt or not operating capacity at the end of the simulation). The reader is again directed to Appendix 9D for explanations of the statistical significance levels quoted.

Table 2.4.1 shows that simulation scenarios with firms of worldview IV (Hierarchist), with 16 firms (instead of 4), and maximum plant scale 400 (instead of 100), all produce more competitive industries. That is, they lead to greater concentration (more of the industry capacity in the hands of fewer firms), higher mortality (more firms go bankrupt) and lower production costs. (There is an exception to this last point in the 16 firms industry case, where the average plant scale is smaller than in the 4 firms scenarios. This gives less chance of cost reduction through static scale economies.)

An initial interpretation of these findings would be that, as expected, the more aggressive IV strategies produce a more competitive situation because of their greater tendency to pre-empt increases in demand. The greater availability of scale economies when production units are allowed to grow to output 400 explains the greater competitiveness in these cases, and this was expected. The 16 firm cases provide greater pressures than the 4 firm industries; this might be explained in terms of "overcrowding", i.e. there isn't sufficient demand to allow all 16 to operate maximum possible scale production units, so that those who get there first achieve cost advantages which the laggards are unable to imitate.

A slightly surprising discovery, however, is that higher industry concentration seems to be associated with Low capital intensity. Plant scales are unaffected. The expectation was that a more competitive situation would arise when capital intensity was high, due to the greater relative importance of capital scale economies. This point is explored more deeply in section 2.5.2 below.

2.5 Analysis of Runs with Technical Change

We now move on to consider the larger body of results of simulations in which technical change was permitted to the firms. These runs were performed over the three different demand series (see Figure 2.1). The results are first considered in comparison with the runs without technical change (section 2.5.1). They are then analysed in their own right (section 2.5.2). Finally, the differences between results for demand series A, B and C are examined (section 2.5.3).

2.5.1 Comparison with No TC Runs

The runs in which firms were not permitted technical changes (section 2.4 above) were all performed using demand series A. A comparison is therefore possible between these runs and those which permitted technical innovations (scaleup and cost-reduction) to the simulated firms where demand series A was employed.

The comparison is made in Appendix 9D. The differences between runs with and without technological improvements are easily summarised; they are all highly significant statistically (all well above the 0.1% level). The runs with technical change produce:

- lower production costs and prices
- higher industry concentration
- higher levels of mortality (bankruptcies)
- larger plant sizes

These findings are as expected. The possibility of technical improvements leads to a new source of increasing returns in the form of cost reduction for successive plants. It also gives the potential for ultimately bigger plants, and hence greater economies of scale, through scale-augmenting innovations. This immediately explains the lower costs and larger plant sizes found.

The higher industry concentration and increased incidence of bankruptcies is a consequence of the asymmetrical nature of the sources of increasing returns. That is, "someone always has to be first" to find a cost-reducing improvement, or to build a bigger plant, and they gain a differential advantage over their competitors. (This process was described in section 2 of Chapter 7.) This is in turn due to the fact that the model takes account of the argument of Chapter 4 that technological innovations are in some (possibly only temporary) sense the "property" of the innovator.

The correlation between technological progress and industry concentration revealed by the comparison of this section is significant, in that it confirms the so-called "Phillips hypothesis". (Phillips (1971), Dosi (1984). See also Chapter 2, section 7.5 above.) This says that high levels of industry concentration should be interpreted as the consequence of past innovatory success. It is an argument against concluding that highly-concentrated industries lead to higher levels of innovation, as some observers have claimed. Thus we have:

Result 1: Technical innovation is associated with higher levels of industry concentration. Simulation runs in which firms were able to make technological innovations had more capacity controlled by fewer firms than runs without the possibility of innovations.

2.5.2 Analysis of Technical Change Runs

The full listing of output measures for all technical change simulation runs is given in Appendix 9B. The comparisons, following the methodology of section 2.3 above, are listed in Appendix 9D.

The following Table 2.5.2.1 shows the significant effects of the key experimental variables upon the output measures. It consolidates the results from all three demand series. (The question of the validity of this consolidation is addressed in section 2.5.3 below.)

Table 2.5.2.1: Summary of Influence of Experimental Variables Upon Key Industry Performance Measures - Simulation Runs with Technical Change

	Influence (alternative)			
Performance Measure:	Worldview IV (II)	16 Firms (4 firms)	Plant Size 400 (size 100)	High Capital Intensity (Low)
Production Costs	---	++	---	+++
Industry Concentration	+++	+++	+	---
Mortality	+++	+++	+++	---
Plant Sizes	+++	---	+++	---
Technological Progress - K	+++	--	---	+++
- L	---	--	---	.

KEY: +++ (---) positive (negative) influence, significant at 0.1% level
++ (--) " " " " " 1% "
+ (-) " " " " " 5% "
. no statistically significant influence

It can be seen (compare with Table 2.4.1) that the influences observed from the runs with no technical change are generally preserved when technical change is allowed. That is, "competitiveness" within the simulated industry is generally enhanced by firms with worldview IV, by more firms in the industry, by higher initial plant maximum sizes and low capital intensity production technology. By "competitive" is meant some or all of: higher industry concentration, greater rates of mortality, larger plants, and lower production costs.

Superior technological progress is represented by negative (-) indicators in Table 2.5.2.1. (A smaller coefficient represents lower costs.) Two factors seem to encourage more successful innovation. The first is the presence of 16, instead of 4 firms in the industry. Since innovation is a series of trials by individual firms, this effect is explicable in terms of the greater number of seekers for innovation that the 16 firm cases produce. The second beneficial influence on reducing K and L is setting the initial maximum plant scale to 400. The likely reason for this is that firms do not expend so much effort on searching for scale-augmenting innovations; they therefore devote more effort to reducing the cost coefficients K and L.

The bias of cost-reducing innovations is as expected i.e. IV's produce better L-reducing innovations, whilst II's reduce K more successfully. This is in accordance with the innovation-seeking rules set out in Chapter 8, section 2.2.

A surprise comes from the High/Low capital intensity influences. The effects upon the output measures are not what was expected. Table 2.5.2.1 shows that there is a highly significant association between Low capital intensity and increased industry concentration, mortality of firms, and bigger plant sizes. (The production cost and technological progress - K effects are both due to the doubling of capital costs in the High intensity runs, and are not otherwise noteworthy.)

It is worth re-stating the assumption here: the High capital intensity scenarios start with a production technology with plant capital construction costs the size of those in the Low intensity case. (Refer to Appendix 9A.) It was expected that scale economies in construction costs would become a more important factor in the High capital intensity runs. To construct a new plant, a firm must forecast a positive NPV for the project. (See Chapter 8, section 5.) If capital construction costs are doubled, then this NPV becomes harder to achieve. Intuition suggests that one effect of this might be to increase the viable minimum economic scale of new plants, since firms would need to exploit the potential economies of scale to offset the extra investment required.

Clearly this does not happen (or, if it does, it is submerged by a stronger opposite effect). A different interpretation is possible: because plants are less expensive to build in the Low intensity scenarios, it is cheaper to build large plants. It might be that large scale plants become viable at lower forecast capacity utilisation levels than in the High cost case, and that big plants are therefore more likely to be constructed. This would suggest that low capital intensity encourages large scale plants, which then produce higher industry concentration.

Scaling up plant sizes brings greater relative economic benefits to a firm in the High capital intensity regime than in the Low. Table 2.5.2.2 shows this:

Table 2.5.2.2: Comparative Total Costs per unit of output for High and Low Capital Intensity Production Technology

	Plant Scale				
	50	100	200	400	800
Costs					
High K = 100	12.87	10.66	9.12	8.03	7.26
%age redn	0.0%	17.2%	29.1%	37.6%	43.6%
Low K = 50	11.33	9.41	8.10	7.20	6.58
%age redn	0.0%	17.0%	28.5%	36.4%	41.9%

Note: in accordance with Chapter 8, section 3.1, equation (34), total production costs are given by:

(0.1 * Capital Cost) + (Labour Cost) + (Variable Cost * Output)

This Table shows that the High K technology gains a definite (if small) relative cost advantage in scaling up production plants. It shows that there are greater cost advantages for firms in the High capital intensity scenarios in increasing plant scale. These simulation results show conclusively that the runs in which the economic (cost) advantages for large plants are greater are not the runs in which the largest plants are constructed:

> **Result 2: The simulation scenarios from which the largest plant scales emerge are not those which would enjoy the largest relative economic (cost) benefits from building bigger production units.**

There is thus the possibility that non-cost factors have an important role in determining industry structure and plant sizes. Pre-emption and market share might be such factors. This question will be considered more fully below. For the moment, note that Result 2 begins to cast doubt upon the familiar argument that large production plants are built because they are economically necessary on cost-reducing grounds. Here we have an example in which larger plants emerge from the situations in which the cost advantages are relatively less important.

2.5.3 Differences between Demand Series

The analysis for section 2.5.2 assumed that it was valid to consider the results from all three demand series together in assessing the influences of the other experimental variables. There are two issues here. Firstly, do the three different demand series give the same results, in the sense that the same experimental variables have similar effects upon the output measures, whichever demand series is used? Only if this is the case is it reasonable to consolidate the results from the three demand series. The second issue is whether there are differences in the results when comparisons are made on pairings which contrast the demand series and hold all other experimental variables constant. In the first case we see whether comparing run 4H1IVA with 4H1IIA gives the same result as comparing 4H1IVB with 4H1IIB. In the latter case we compare 4H1IVA with 4H1IVB, 4H1IIA with 4H1IIB and 4H1IIC, and so on. (See section 2.1 above for definitions of the run codes.)

The first question is easily answered. Appendix 9D lists the non-parametric comparisons for each demand series, as well as for the sum of the three. It is possible to test the differences statistically, although an inspection of Appendix 9D by eye shows that in the majority of cases it is obvious that there is no difference between the results for different demand series. Appendix 9E describes the Chi-squared goodness-of-fit test carried out to show that this is indeed the case. The result is that, out of the 56 cases, only 2 failed the test at the 5% level of significance and one failed at the 1% level. Given that 1 out of 20 would be expected to fail the at the 5% level and 1 out of 100 at the 1% level by pure chance alone, it is safe to conclude that the relationship between input experimental variables and output performance measures is essentially independent of the demand series used.

The second question involves comparison of the output measures where the variable experimental factor is the demand series employed. The full comparison is given in Appendix 9F.

(The demand series are shown in Figure 2.1 above. B is roughly twice the size of A at all times; C starts higher than A and B, but grows slowly so that it ends at about the same demand level as A.)

Significant differences do appear between the demand series:

<u>Plant Scale</u> is considerably greater in demand series B than in either A or C. This is probably because there is more "room" for big plants where demand is higher.

<u>Mortality</u> is higher in A and B than in C. This may be because less dramatic change (growth) occurs in series C.

<u>Costs</u> are highest in C, then A, then B. B probably has the lowest costs because of its larger-scale production plants.

Suggestions as to cause and effect are left intentionally tentative: more work, on a wider variety of demand series, is needed before safe conclusions can be drawn about the effects of particular demand series upon the output measures. However, the significant differences observed here demonstrate that industry structure is affected by market size - at least within the EMIR simulation model.

Result 3: Plant scales and industry structure do not evolve independently of the size of the market.

Expressed like this, the result is almost banal. It is, however, important because of the old economic maxim, encountered in Chapter 2, that "the division of labour is limited by the extent of the market". For "division of labour" (Adam Smith's words) substitute the more prosaic "plant size economies of scale", and we see that EMIR is in agreement with one of the oldest strands of classical economics.

2.6 Regression Analysis of Industry Structure

The results obtained in section 2.5 have been based upon individual comparisons, with only one influence varying at a time. A more complex representation of influences of simulation outcomes would predict outcomes by allowing the effects of the several factors to vary together. This can be done by using multiple linear regression, with dummy (0/1) variables for each of the experimental factors and demand series. A simple additive linear model is used; the objective is to confirm qualitative effects, not to find the ideal functional relationship between inputs and outputs.

Appendix 9C reports the "best" equations derived by stepwise regression. It presents results which are in close agreement with those found by examining single influences in section 2.5. The explanatory power of the regression equations ranges from very respectable to disappointing (R^2 of 80% to 27%); however, all reported coefficients are significant at least at the 5% level. The signs of all significant regression coefficients are in agreement with Table 2.5.2.1 above.

The dummy variables for demand series do enter the regression equations in some cases, confirming that there are significant differences between results for some output measures. Again, the regression equations agree with the findings of section 2.5.3 above on this point.

It can therefore be concluded that the influences identified by looking at the effects of changing single experimental variables are preserved when we vary several factors simultaneously. There do not appear to be important interaction effects between variables which have been missed by the single-variable comparisons of section 2.5. The influences are summarised again in section 2.7 below.

2.7 Preliminary Conclusions

In section 2 we have looked at the main set of experiments with EMIR. The relationship between the experimental variables and the output performance measures are summarised below in section 2.7.1 and 2.7.2. Some implications are briefly discussed in section 2.7.3, where some questions for further enquiry are introduced.

2.7.1 Output Measures

The influences upon the main performance measures, taken at the end of the simulation runs, are as follows:

Production Costs are lower where firms have adopted the more aggressive IV-worldview, and where the initial maximum plant scale is set at 400, allowing earlier exploitation of economies of scale. Costs are higher in the simulated industries with 16 firms, probably because of the existence of fewer opportunities to build large-scale plants. (High capital intensity automatically increases production costs.)

Industry Concentration is increased by the IV-worldview, and by Low capital intensity production technology. It is also increased in the industries with 16 instead of 4 firms; there would seem to be less "room" for more firms.

Mortality of firms goes up with worldview IV, with 16 firms, and with the starting plant scale set at 400. It is lowered with High capital intensity, i.e. mortality is higher in the low capital intensity scenarios.

Plant Sizes are found to be larger in the IV-worldview cases and, not surprisingly, in the runs where the initial maximum scale is at the higher level of 400. They are lower in the 16-firm industries; again the problem of "enough room" is a plausible explanation. Plant scales are found to be bigger in the Low capital intensity situations than in the High.

Technological Progress is biased towards reducing operating costs (L) by the IV-worldview and towards lowering capital construction costs (K) by the II's, as expected. In general, technological progress is more successful in improving (lowering) both K and L in the 16-firm, high (400) initial plant scale and Low capital intensity cases.

2.7.2 Input Experimental Variables

The selected experimental variables have the following effects:

Technical Change has a very strong influence in increasing the competitiveness in a simulation run. It raises plant scales, lowers costs, and leads to higher levels of concentration and mortality.

Worldview is also important in determining the competitiveness of a scenario. The more agressive IV's build bigger plants, and similarly lower their production costs, increasing concentration and mortality among competitors.

Number of firms in the industry has a lesser influence. The runs with only 4 firms (instead of 16) yield larger plants, and this accounts for their lower costs, despite their poorer progress in improving production technology. The 16 firm cases bring about higher relative concentration and mortality rates.

Initial Plant Scale feeds into the final plant scales observed in these runs. The cases which start with high maximum scale end up with larger plants, and also lower costs. They also succeed in improving their production technology further than in the runs with a lower initial maximum; this may be because more innovative effort has to be devoted to scaling up by the firms in the latter.

Capital Intensity has a paradoxical effect, in that Low intensity starting technology produces more competitive industry regimes, with bigger plants, higher concentration and higher mortality rates.

Demand Series do produce different effects. However, in each of the three demand scenarios used here the influences of the other experimental variables are invariant. Not surprisingly, it seems that higher demand leads to larger plant scales. However, more work would be needed before convincing conclusions about the effects of different demand scenarios could be drawn.

2.7.3 Discussion of Results

As the simulation results have unfolded, the theme of "competitiveness" has emerged. By a "competitive" industry scenario is meant one in which industry concentration is high (a few firms control the market), mortality rates are high (significant numbers of firms are driven out of business), large plants are constructed, production costs tend to be lower and the rate of technological progress tends to be quicker.

The major surprise from these experiments has been that the Low capital intensity situations produced larger plants, despite the fact that the High intensity technology offers greater relative economic benefits for building big production units. What seems to matter is how easy it is for a firm to build a big plant (or several big plants), and what seems to matter less is the total magnitude of the cost savings to be achieved. When capital intensity is low, big plants can be erected less expensively, and firms which take the risk of building big are less likely to suffer an early demise through the weight of the extra debt burden. This, at least, is a possible interpretation.

These preliminary experiments thus lead to the hypothesis that pre-emption and acquisition of market share are more important indicators of a fiercely competitive industry than the existence of substantial technological economies of scale. The emergence of a small number of firms, or of only one, is likely to be associated with conditions where firms engage in what might be compared to a military contest for territory. Once territory (market share) is gained, increasing returns will strengthen the dominant firms' position by allowing them a faster rate of technological progress and greater relative exploitation of economies of scale. The aggressive and successful strategies, and those situations and technologies which facilitate the greatest exploitation of increasing returns, are also those which carry the highest risks and the greatest mortality rates for the unsuccessful.

Economists have made several attempts to explain market and industry structure in terms of economies of scale. A notable study was Scherer et al's (1975) analysis of industrial concentration in 12 industries across siz different countries. Static production cost economies of scale were found to be relatively poor predictors of concentration and of plant and firm size. Clearly, a wide range of other factors affects concentration in these industries. However, the EMIR simulation results indicate that, even in principle, the fact of the existence of economies of scale in production should not be expected automatically to produce higher levels of concentration than in industries without such scale economies. Indeed, EMIR has shown a counterexample, in which simulated industries with lower economies of scale yield higher eventual concentration.

In order to further investigate the issue of "competitiveness" and the possible role of market share as an important source of competitive success, further analysis of the simulation data is carried out in section 3 below.

The effects of "competitiveness" upon the individual firm are worth investigating further. Worldview IV produce more competitive industry scenarios; what happens when firms of worldview II and IV are placed in direct competition with one another? Section 4 examines this question.

Finally, again from the viewpoint of the individual firm, what are the consequences of adopting a more aggressive strategy? The competitive situations certainly produce more casualties. The effects upon the eventual fruits for the winners of the fiercer battles are investigated in section 5, where individual firms' profitability levels are analysed.

3. THE IMPORTANCE OF MARKET SHARE

It has been suggested above that market share is an important factor in achieving competitive success in EMIR. High market share allows the leading firm to build larger plants (because it can rationalise its own capacity by replacing a number of small old plants) and thus gain cost advantages through economies of scale. Market share also helps in gaining technological progress; building more plants allows more innovations to be tried out more quickly. In these complementary ways the two sources of increasing returns in EMIR are exploited.

To confirm the hypothesis (that market share is important for competitive success), we need to show that:

(a) runs in which there are high levels of increasing returns available to firms (e.g. the technical change runs) show more pronounced advantages for firms which gain market share than runs with lower levels of increasing returns (e.g. the no technical change runs).

(b) gains in market share tend to be maintained for long periods.

(c) passing a "threshold" market share proportion allows a firm dominance for some time.

These points are examined below in sections 3.1 to 3.3. ((b) and (c) would be consistent with market share being a source of advantage, although they would not prove it by themselves.)

In order to compare market share effects, a number of new output measures were paired and averaged over the runs. These were:

(i) the number of periods for which the "winner" at t=59 (i.e. the firm with largest market share) had been "winning";

(ii) the number of periods for which the winner had had either the largest or second largest market share;

(iii) the market share which the winner needed when it first gained the dominant ranking;

(iv) the proportion of time for which the current leading firm had operated a larger plant than its rivals whilst it had been the leader;

(v) the "thresholds" which firms typically needed to achieve in the simulated industry in order to become market leader for at least 10 periods.

The motivation for choosing these measures was that (i) and (ii) give an idea of the persistence of market share leadership. (iii) and (v) tell us what constitutes a "significant", large market share. (iv) measures how much of the time market share and large plant scales are associated for winning firms.

The full data set is given in Appendix 9G. The following is a summary of the analysis given in Appendix 9H. Note that only simulation runs with 16 firms were considered; the 4-firm cases would have yielded more volatile results and, in any case, would have required high market shares for dominance, by definition.

3.1 Market Share and Technical Change Effects

As noted above, the "No Technical Change" (NTC) runs were performed with demand series A only. We can compare them with the "Technical Change" (TC) runs for series A (Table 3.1.1):

Table3.1.1: Comparison ofMarketShare EffectsWithandWithout Technical Change

	No Technical Change	Technical Change
Average time at which winner took 1st place	44	32
Av. Market share of winner on taking 1st place	21%	34%
Av. proportion of time for which winner had biggest plant in industry	28%	84%

Statistical significance for the averages of Table 3.1.1 is established in Appendix 9H. The comparison shows that the winning firms in the TC runs had been both the leader, and one of the top two firms by market share, for signifcantly longer than the winners in the NTC scenarios. The TC firms required significantly larger market share initially to gain first position. The winning TC firms operated a larger plant than any of their competitors much more frequently compared with the NTC firms. (Too much weight should not be placed on this last result, however; because of the limits to scaleup in the NTC runs it is likely that several firms would be operating maximum size plants.)

A comparison of market share "thresholds" also showed significant differences. Table 3.1.2 summarises the chances of a firm, having achieved the indicated market share threshold, being one of the two largest firms in the industry for at least the following ten periods:

Table 3.1.2: Probabilities of a Firm Being One of the Two Largest in the Industry in the Ten Periods After Achieving a Given Market Share (Demand Series A Only)

Market Share Threshold %	No Technical Change	With Technical Change
20	33.3%	42.7%
25	28.9%	54.4%
30	54.3%	78.8%
35	65.0%	88.9%
40	83.3%	(100.0%)

Table 3.1.2 shows that TC firms which gain a market share advantage are more likely to maintain it. A 30% market share, for example, will give an NC firm about a half chance of being in the top two for at least ten more periods; a TC firm will have almost a four-fifths chance. This is in accordance with the argument that market share is important in exploiting the increasing returns which come from technological innovation. Once market share is gained, it is more likely to be kept if it can be used to bring about cost reductions through additional technical changes. (See Appendix 9H for statistical significance.)

We therefore conclude that, where there is the potential for technological improvements, winning firms emerge sooner, and maintain their position for longer. Obtaining a "threshold" market share is associated with prolonged competitive success significantly more often in the presence of technical change.

3.2 Market Share of Winning Firms

In this section we consider only simulation scenarios with technical change present.

Overall, the average winning firm at t=59 had already emerged at t=32, with a market share of 29%. It had been one of the top two firms since t=24 (when it had a 19% market share). While it was the number one firm by capacity, it had operated the largest plant in the market for 69.5% of the time.

There were differences in results for different experimental scenarios. Table 3.2.1 summarises some of them:

<u>Table 3.2.1: Influences of Experimental Variables Upon Market Share Effects</u>

	Influence (alternative)		
Performance Measure:	Worldview IV (II)	Plant Size 400 (size 100)	High Capital Intensity (Low)
Time winner emerges	earlier	same	later
Winner's first mkt share	higher	higher	same
Winner owns largest plant	more often	same	same
Success thresholds	similar	higher	similar

Note to Table 3.2.1: Words rather than symbols are used to avoid confusion over the sign of effects. "Same" or "similar" means the effect is not statistically significant; otherwise, it is significant at least at the 5% level. Consult Appendix 9H for more details.

It is clear that the situations which were identified as "competitive" in section 2 have common characteristics in Table 3.2.1. That is, the worldview IV, initial plant maximum scale 400 and Low capital intensity scenarios all tend to produce their eventual winners earlier, with larger market share as they emerge.

The conclusion to be drawn from this is that, in the more "competitive" situations, being a winner is associated with gaining a leading position early. Once gained, market share tends to be held. The market share required by the ultimate winner is larger than in the less competitive regimes.

No significant differences were found between market share results for the three different demand series, except that firms in A required a higher share to first emerge as winners than firms in B. The times when winners first appeared were similar in all cases. Threshold success and failure probabilities were not statistically different.

This is reassuring; it might have been objected that the persistence of market share was simply due to "natural" autocorrelation, which could be present even if firms added capacity randomly. However, the rates of demand growth are quite different in the three demand series A, B and C, so the similarity of the results makes the purely "statistical" autocorrelation argument implausible. (If the demand level is fairly constant then plant builds occur less frequently, which under the "random" explanation would make market share leadership much longer-lasting than in demand scenarios with rapid growth. The absence of such a difference undermines this explanation.)

3.3 Threshold Market Share for Success

Table 3.3.1 shows that achieving a 30% market share guarantees a spell of market dominance for a firm about four times out of five:

Table 3.3.1: Chances of Failure and Success in Maintaining a Position In Top Two For 10 Periods After Achieving Market Share Thresholds

Market Share Threshold (%)	Failures	Successes	Percentage Success Rate
20	108	102	48.6%
25	56	100	64.1%
30	22	86	79.6%
35	10	79	88.8%
40	2	60	96.8%
45	1	50	98.0%
50 +	2	65	97.0%

Note: Table 3.3.1 shows results for all Technical Change runs, all demand series.

The percentage success rate shown in Table 3.3.1 is very similar to that in Table 3.1.2 (Technical change runs, demand series A only).

3.4 Conclusions on Market Share Effects

It has been shown that a firm which obtains a market share of 30% is very likely to remain one of the top two firms in the industry for at least ten periods. Moreover, firms which held the dominant position at the end of a simulation run had on average held that position for nearly 30 periods.

There is thus evidence that market share, once gained, tends to be held. Comparison between results for No Technical Change and runs with Technical Change demonstrates convincingly that the ability to make technological improvements is an important cause of this (section 3.1).

> **Result 4: Market share is important for competitive success, because it permits greater exploitation of increasing returns.**

In scenarios identified as being more competitive the eventual winners emerge earlier than in the less competitive situations. These competitive situations - the IV-worldview, the starting maximum plant scale 400, and the Low capital intensity technology - have in common that they allow or encourage early capacity expansion. (The IV's are generally more aggressive, and plan for a larger margin of overcapacity; 400 initial plant scale permits larger plants to be built generally; Low capital intensity similarly makes it easier to build large units - see section 2.7.3.) The fact that these situations produce earlier winners is additional support for the argument that the acquisition of market share is a key ingredient for success under increasing returns. (The sources of "increasing returns" in EMIR are both technological progress and economies of scale.)

Increasing returns through technological improvements are well-known in a slightly different form as the "Progress Function" or Learning Curve;

firms seek greater market share so as to achieve progressive cost reductions from cumulative output from each plant. This approach to business strategy was popularised by the Boston Consulting Group (BCG 1965). Economists have taken account of them in some relatively sophisticated analyses of competition - see e.g. Spence (1981). However, progress effects in capital goods and exploitation of scale economies are not generally accounted for in microeconomic models, although they are well known to business policy analysts (see the survey by Dutton and Thomas, 1984). As noted in Chapter 2, increasing returns disappeared from the analysis of almost all "political economists" after Marshall.

In support of these simulation findings, there is some evidence that Japanese companies in particular have pursued the size/market share route to competitive success in recent decades. There is considerable anecdotal evidence that Japanese managers have been keen to construct the largest possible plants even when their technical experts told them that the available economies of scale did not warrant it (see e.g. Gold 1974). Abbeglen and Stalk (1985) report a survey of Japanese executives in top 500 firms which found that they regarded market share as the most important corporate objective. A comparable group of US executives rated both return on investment and share price increase as more important.

Clearly there are many factors besides those of scale and market share which have made Japanese companies internationally successful. Nevertheless, these results are in encouraging agreement.

4. COMPETITION BETWEEN THE WORLDVIEWS

It has been shown that there is a strong association between "competitiveness" and the IV-Hierarchist worldview in EMIR. It has also been shown that simulated industries with the IV-worldview (as well as others) are associated with the most successful firms gaining a dominant position early, and successfully holding it.

No strong conclusions have been drawn from the association between competitiveness and the tendency for winners to emerge earlier. It might be argued that this association of phenomena is spurious correlation (despite the specific attributes of the IV-worldview strategy which make it a plausible relationship - see Chapter 7, section 6.2). It could be that "competitiveness" (which has been measured by looking at resultant industry concentration, plant sizes and costs) naturally implies that firms stay dominant for a long while. Industry concentration is naturally highest, in the most extreme case, when only one firm survives.

However, we can test whether the IV-worldview does indeed lead to competitive success directly. By simulating an industry in which some firms have the IV-worldview, and others the II-worldview, we can see whether the configuration identified as more "competitive" is actually more successful in practice.

To do this, the model was run a number of times (16 in all) with eight firms having worldview II and eight having worldview IV. The demand series was A, and the scenarios were High and Low capital intensity, initial plant maximum scale 100 and 400. Each scenario was run four times with different random number seeds, as usual. At the end of each run the number of firms still operating plants, not operating any capacity, and bankrupt, were recorded (see Appendix 9I). Table 4.1 summarises the results:

Table 4.1: Results of Competitions Between the Worldviews

Run		Average Number of firms at t=59: Operating	Not Operating	Bankrupt
16 H 1	IIs	0.00	5.00	3.00
	IVs	3.50	1.25	3.25
16 H 4	IIs	0.25	4.50	3.25
	IVs	2.00	0.50	5.50
16 L 1	IIs	0.00	6.25	1.75
	IVs	4.00	2.50	1.50
16 L 4	IIs	0.00	7.25	0.75
	IVs	2.75	2.50	2.75

Table 4.1 shows very clearly that the IV's have a considerable competitive superiority. In only one simulation out of the 16 did a single II-firm have any operational plants at all at the end of the run. (The probability of this happening by chance would be less than 0.0003 if there were no difference between the competitive "fitness" of the two worldviews.)

From this, we can conclude that the greater competitiveness of the IV's, initially measured through the industry structure observed as an outcome of simulation runs, is a genuine behavioural trait. The tendency for winners to emerge early and maintain their lead is thus due to their superior ability to fight for market share, and hence exploit increasing returns effects. Adoption of the IV-worldview by a firm does give it a relative competitive advantage, in the sense of improving its chance of being a winner. (It may also improve its chance of coming to an untimely end - see section 2.5, where Mortality is shown to also increase with worldview IV.)

Result 5: The IV-worldview competes aggressively (and successfully) by encouraging firms to gain market share early.

5. PROFITABILITY OF FIRMS

Whilst survival may be seen as the first aim of any actor in an industry, the profitability of a firm is the next most important thing to consider. We can examine this in EMIR by looking at the amounts of accumulated capital held by the firms at the end of the simulation run. The detailed results are presented in Appendix 9J, and the paired comparisons in Appendix 9K. They are summarised below in Table 5.1. This shows the influences of the experimental variables upon the profitability of the industry. The performance measures are: the total profit (accumulated capital less any debt) of the firm with the largest capital; the winner's percentage share of the total capital for all firms; and the total for all firms in the industry. (NB 4/16 firms comparison omitted, because the total profitability measure is distorted by the number of firms - see note in Appendix 9K.)

Table 5.1: Influences on Firms' Profitability

	Influence (alternative)		
Performance Measure:	Worldview IV (II)	Plant Size 400 (size 100)	High Capital Intensity (Low)
Winner's Total Profit	---	.	.
Winner's Profit as % of total	+++	.	---
Total Profits of whole industry	---	---	+++

KEY: +++ (---) positive (negative) influence, significant at 0.1% level
++ (--) " " " " " 1% "
+ (-) " " " " " 5% "
. no statistically significant influence

The most competitive situations are those with worldview IV, initial plant scale 400 and Low capital intensity. In the first (worldview IV) of these cases the most successful firm is shown in Table 5.1 to be significantly less profitable than in the corresponding less competitive case. In the other two sets of comparisons the difference is in the same direction (i.e. the more competitive scenario yields lower absolute profitability for the winner more frequently - see Appendix 9K), but the difference are slightly below statistical significance at the 5% level.

On the other hand, the percentage share of profits gained by the winner in the more competitive situations was significantly greater in two of the cases (worldview IV and low capital intensity). The percentage share in the 400-firm scenarios tended to be larger, but the difference was again not quite significant at the 5% level.

Finally, two out of the three predictors of competitiveness (IV-worldview, and low capital intensity) give significantly lower total profitability for all firms in the industry.

In agreement with these results, a comparison between profitability for runs with and without technical change (on demand series A only) shows much higher profitability for the winner, but lower profits for the industry as a whole. Thus the situation with the greater degree of increasing returns gave comparatively better results for the winner, but absolutely worse results for the industry as a whole.

> **Result 6: In the more competitive situations successful firms gain a larger share of the industry profits, but these profits are often not so great as in less competitive situations.**

So striving too hard for competitive success, as well as leading to higher rates of bankruptcy (see section 2) may depress profitability. Trying too hard to dominate the market may simply lead to a worse result for everyone, including the aggressive "winner". For a good real-life example of this effect, see Ghemawat's (1984) study of competition in the Titanium Dioxide Industry.

6. CONCLUSIONS

The results can be considered in terms of the implications for three perspectives: those of the Theoretician, the Policy Analyst and the Decision-Maker.

6.1 Theoretical Implications

In summary, the key theoretical findings from these experiments with EMIR are as follows:

1) Most importantly, part of the reason for building a model such as EMIR was simply to show that it can be done, and to suggest that this is the most fruitful path for further study of microeconomic interactions. The model has succeeded in that aim; its behaviour is certainly no less realistic than any other traditional microeconomic description, and in many ways its workings are built much more closely upon observations of how economies of scale, technical change, information, bounded rationality and learning actually work in the real world.

2) Within this model, economies of scale do not automatically lead to large plants or highly-concentrated industries by themselves. Indeed, Result 2 shows that there are cases where the opposite is the case. Simulation runs have shown situations in which relatively lower degrees of static scale economies can lead to higher degrees of industry concentration.

3) A corollary, and the most surprising discovery from the experiments with EMIR, is that the relative magnitudes of scale economies are not the most important determinants of industry concentration. The conventional theorist's objection to including economies of scale in a model at all has been that it would imply accepting that an industry would have to be dominated by 'economy of scale' plants i.e.

by production units with the lowest possible production costs. This does not occur in EMIR. On the contrary, the high capital-intensity industries (which could enjoy the greatest economies of scale in production) tend to have smaller plants on average.

4) The implication of 2) and 3) is that it is no longer especially surprising that economists have not been very successful in explaining industry structure in terms of static economies of scale (e.g. the important Scherer et al (1975) study - see discussion in section 2.7.3). EMIR provides a model which shows why such an explanation will need to be more complex.

5) Among other influences (outside the scope of EMIR), industry structure is in fact affected by other sources of increasing returns, and especially by technological change. EMIR shows that technical change can be at least as great an influence as static production cost economies of scale (Result 1). The worldview of firms is another key factor (Result 5).

6) Moreover, industry structure and plant sizes are not independent of the size of the market (Result 3).

7) The model has provided confirmation of Phillips' hypothesis (Phillips 1971) that industry structure is a function of past innovatory successes; this has important implications for the validity of a number of studies of the firm size-innovation rate relationship (Result 1).

6.2 Policy Implications

The policy analyst is most interested in those forces affecting competition in an industry, and in understanding whether intervention is needed to improve the economic system. Clearly, there is a considerable leap involved in going from EMIR simulation results to prescriptions for the real world. The following is suggested as the kind of advice that such a model can provide:

1) Economies of scale are not a good predictor of concentration (Result 2). It follows that, if the existence of considerable technical or production scale economies are not automatically a compelling factor in inducing industrial concentration, their use as arguments in favour of allowing high degrees of concentration should be viewed with suspicion. (The survey of empirical studies in Chapter 2 bears this point out.)

2) Market share leads to market dominance. In the absence of other influences (of which there might be many, of course), if a firm gains a substantial advantage in market share it is likely eventually to dominate the industry. The dominant actor can produce more frequent technical improvements and economy-of-scale plant rationalisations, squeezing out "marginal" competition by reducing costs. (Result 4). Growth in this oligopolistic competition is the result of successful move and countermove against opponents, not of the fine-tuning of price and demand elasticity curves. A military contest for territory is a fair metaphor for this process. Pre-emption of capacity, as practised by the IV-strategists, seems to be an important competitive weapon, allowing technological learning and the utilisation of static economies of scale.

3) High degrees of competition in an industry for prolonged periods are not good for its health (Result 6), leading to perhaps unsustainably low profitability.

4) The theoretical points 6 and 7 above - that industry structure

evolves as a result of endogenous forces as well as external influences - should be thoroughly absorbed by the policy analyst as well as the theorist. The discovery that firms with a particular structural characteristic (e.g. big firms) also have another desirable characteristic (e.g. they are good at innovation) should not lead to the automatic conclusion that policy prescriptions which encourage the one will also stimulate the other (e.g. if we encourage firms to merge and thus become bigger they will become better at innovation). Past success may lead to size; it does not follow that size causes success unless, as in 2) above, there are particular reasons why further increasing returns are available to the larger firm.

6.3 Implications for the Decision-Maker

The chief lessons for the decision-maker are:

1) Market share is more important than immediate profitability, because market share will determine ultimate survival and profitability (Result 4). Thus decisions on capacity increases, pricing, and marketing plans should be geared to gaining long-term market share rather than short-term returns. That is, pre-emptive building of production capacity can pay off in the long term even though it may not yield profits immediately. The dynamic nature of the environment of the firm, in which other firms, their plants, and their production technologies are all subject to change, growth and evolution, means that it is the potential for future performance which matters.

   This conclusion is reinforced in EMIR by the success of the Hierarchist IV-strategist over the II-Sectists (Result 5). The IV's take a much longer planning horizon, using a lower discount rate, and "win" all the simulated industry competitions against the more cautious short-term II's.

2) The risk of this strategy is that over-competitiveness spoils the market for everyone (Result 6). The corollary, then, is that one should be willing to consider cutting losses and investing in other areas once it has become clear that other firms have prevented you from attaining a dominant position in the market.

6.4 Further Work

This chapter has concentrated on issues of cost, plant size and industry structure. In the next chapter EMIR is used to investigate an important issue in the development and selection of technology. In the final chapter the broader implications of this type of model will be discussed, and put into the context of the rest of the thesis. In conclusion, there are areas worthy of further investigation:

1) Clearly, the particular details of the outcomes of a given simulation run are dependent upon more than the experimental variables and demand series which have been highlighted. The detailed description of the model in Chapter 8 shows that a range of parameters have been "hard-coded" into the model. They deal with things like the probabilities of innovations, the exact specifications of the behaviour of firms with different worldviews, acceptable gearing levels for firms, the characteristics of the technologies used, and so on. A full understanding of the model requires further investigation of the effects of varying some or all of these.

2) Having said that, I am confident that the generalised findings condensed into Results 1 to 6 would be preserved under a wide range of parameter choices. This confidence is based upon observation of the behaviour of firms under increasing returns in hundreds of simulation runs. This being the case, an interesting exercise would

be to attempt to reduce this highly complex model whilst still preserving the important facets of behaviour. Exactly which assumptions are important, and which can be simplified? I believe that the innovation search and plant scale choice (investment appraisal) processes could be considerably simplified whilst still producing the same performance effects.

3) Finally, it has been shown that market (demand) size influences plant scale. Further analysis with a wider range of demand series would allow stronger conclusions to be drawn about the nature of that relationship.

Chapter 10: Technological "Lock-In" Through Small Events

1. INTRODUCTION

In Chapter 9 the Evolutionary Model of Increasing Returns was used to investigate conventional questions of industrial competition and structure. In this chapter, the richness of the model is demonstrated by using it to analyse the problem of increasing returns and "technological lock-in". This important economic problem is particularly interesting because it is not addressed at all by any existing techniques in economics.

So far we have concentrated on scale effects to the partial exclusion of questions about technological innovation. This chapter investigates a particular problem in the economics of technical change, demonstrating the power of EMIR to shed light upon a question which other models cannot approach. The problem is first outlined.

2. THE PROBLEM

The "optimising" view of the world holds that rational economic actors will always make the choices which provide the greatest payoffs for themselves. This is a consequence of the belief that, on the average, a group of actors will in the long run behave as if they had perfect information (because the process of trial and error can be relied upon to unearth the most profitable choices). The corollary is that the technologies which exist today must, by the evidence of their very survival, be "optimal" in some sense.

Brian Arthur has argued that this is not always the case. (Arthur 1983.) There exist many examples of technologies which have been universally adopted which clearly do not fulfil the criterion of optimality. A good example is the QWERTY typewriter keyboard, deliberately designed to slow down the typist (because the early mechanical machines became jammed easily). Other plausible cases include: the dominance of the FORTRAN computer programming language over ALGOL; the widespread adoption of light-water nuclear reactors in preference to gas-cooled; and (more controversially) the adoption of the internal-combustion engine automobile in preference to its steam-driven competitors in the early 20th century. (See Arthur 1983, 1987 and references therein for documentation of these claims.)

These cases have two factors in common. One is that their fates were determined by what seemed at the time small, even trivial, "random" effects. (E.g. the development of the steam car in the USA was seriously retarded by an outbreak of foot-and-mouth disease in 1914 which caused all the public horse troughs to be removed, depriving the steam vehicles of refuelling facilities.) The other common feature is the existence of increasing returns to adoption of the technology. This can come about through a variety of causes, including learning through using, network externalities (fit with existing technologies), and economies of scale.

The increasing returns aspects of the "Lock-In" have been investigated mathematically by Arthur, Ermoliev and Paniovsky (1986). EMIR gives us an alternative way of demonstrating the existence of the "Lock-In" phenomenon. EMIR can represent technologies in evolution and competition. It has increasing returns, both through economies of scale in adoption (larger plants cost proportionately less), and through learning-by-using effects. It also possesses a randomness at the micro level, in that the incremental innovation process, and the choice of firm to build the next plant, are both governed by chance features.
Thus it is possible to illustrate "Lock-In" by repeatedly simulating the outcome of a "competition" between two production technologies. This can be done by giving one technology to some of the firms in the model

and a different one to the others. The technologies compete through the firms which build plants using them. "Good" technologies should prosper as they allow their firms to lower production costs, thus permitting them to expand output further and gain greater cost reduction through economies of scale. More plants mean more technical experiments and more chances to improve the favoured technology, which should strengthen its advantage over the inferior rival. Innovation by imitation will mean that firms with the inferior technology will switch to the superior once they realise that better returns can be earned by changing over.

Thus it should be the case that a "superior" technology will be able to win the technological competition of "survival of the fittest", for there will undoubtedly be increasing returns to scale of its adoption. The flaw in this argument, and the problem with this kind of post hoc reasoning is well illustrated by the following experiment.

3. EXAMINING TECHNOLOGICAL LOCK-IN WITH EMIR

Two different technologies were selected. For simplicity's sake, they were both set to have maximum scale of 100 and minimumn of 40, with labour coefficient L set to 100. The first one (technology A) had capital coefficient 100 and variable cost 1.5, whilst the other (technology B) had K and V of 50 and 5.0 respectively. (Refer to Chapter 7 for details of the representation of technology in EMIR.) Thus A has high capital requirement and low variable cost, whilst B has lower capital needs but higher variable inputs.

Bearing in mind the fact that the K and L coefficients can be altered quite significantly by incremental innovations, whilst V can only be improved by very small amounts, it is clear that A has better long term prospects in that it is has the greater potential for overall cost improvements. That is, the high capital requirements of A can be reduced more quickly than the high variable costs of B. The relative costs per unit of output of the two technologies at a range of scales up to the maximum is as follows:

Table 3.1: Comparison of Production Costs for Simulated Technologies A and B at Differing Scales of Production

Plant Scale	40	50	60	70	80	90	100
Costs per unit output:							
B) K=50, V=5	10.467	9.782	9.286	8.908	8.607	8.361	8.155
A) K=100, V=1.5	12.434	11.064	10.073	9.315	8.713	8.221	7.810
Difference	1.967	1.282	0.787	0.407	0.106	-0.140	-0.345

These two technologies were set in competition six times, initialising the random number stream with the numbers 1 to 6. There were 16 firms; eight of them were given technology A to begin with and eight of them technology B. The same demand sequence was run for 59 simulated periods as in the standard experiments described above. The results for the six runs were:

Table 3.2: Results of Technological Competitions

Random Seed	1	2	3	4	5	6
Winner	B	A	A	A	A	A

The superiority of technology A at plant scales greater than 80 meant that it was nearly always the winner of the technological competition. That is, by t=59 (often well before) technology B had been driven out of existence; firms operating it had been driven into bankruptcy, or had avoided that fate by switching to A.

The cost advantage of A was then slightly reduced by raising its V coefficient to 2.0. This implies virtually equal production cost at an output scale of 100 (the initial maximum for both A and B). The results were then as follows:

Table 3.3: Results of Technological Competitions after a Small Relative Performance Reduction in Technology A

Random Seed	1	2	3	4	5	6	7	8	9	10
Winner	B	A	B	A	B	=	B	A	=	B

The final tally is five "wins" for B and three for A, with two "draws"- cases where both technologies were still in existence at t=59. (In both these cases it appeared that A would have been the eventual winner if the run had continued, since it acounted for the major proportion of production and had significantly lower costs.)

4. ANALYSIS OF THE RESULTS OF TECHNOLOGICAL COMPETITIONS

This is an extremely interesting result, despite its apparent simplicity. Firstly, it is clear that a small change in one technological parameter has the effect of completely altering the competitive outcome. A small further increase in the V coefficient of B would lead to its superiority in almost every case. Thus an incremental change in one part of the system (the available technological repertoire) leads to a non-linear, non-incremental jump in the system as a whole. There is an instability near this critical point in the universe of possible technologies, and the system is clearly "non-equilibrium".

Thus in the presence of increasing returns it is not always true that the chances of survival of a particular technology are directly related to the amounts of improvements and development which they enjoy. Relative "fitness" or potential for success is not at all proportional to the absolute difference in performance capabilities; rather, there is a threshold of "fitness" which is passed or which presents an insuperable obstacle.

In the case where two technologies appear to be balanced (such as the second set of competitions above), the balance does not tend to result in an outcome in which two rival technologies co-exist. Increasing returns see to it that, in general, one succeeds at the expense of the other. (This is a good example of what economists call a "non-convexity".) Relatively small events are amplified in importance by the increasing returns phenomenon. The outcome of the simulations in the second set of competitions is quite clearly non-deterministic and rests upon which technology first succeeds in achieving significant scaleup and implementation at the larger scale.

It is worth repeating the comment made in describing the two technologies A and B used for the experiment above. A and B have similar costs initially, but because of the structure of the technology and the nature of the search process for improvements, the potential for reducing costs over time is much greater for A than for B. This does not, however, mean that A always wins the relatively short-term technological competition; it can be completely displaced by B before its potential is realised by the competing simulated firms.

> **Result: Small random events, and small differences in technological specification, can produce completely different outcomes. The winner of a technological competition need not be that technology which would have been most economically beneficial in the long run.**

So the history of a system is very important in explaining and understanding how it came to be as it is. The argument that things are as they are because the present technology is the "optimal" choice is, in these situations at least, quite spurious. The argument, for example, that paper must be manufactured in very large-scale plants rests upon certain technological "facts" which (as we have seen in earlier chapters) are open to dispute. However, even if we accept these "facts", we need not abandon the possibility that it might have been more efficient in the long-run to adopt a completely different technology which does not require large scale for economic operation.

This argument should not be confused by the fact that, in EMIR, an important source of increasing returns is the presence of substantial economies of scale in every technology. It is the increasing returns which lead to the Lock-In phenomenon, and these need not arise from static scale economies alone. The key point is that EMIR demonstrates that the fact of winning a technological competition for survival does not automatically imply "optimality".

(In the real world, of course, the situation is further complicated by the fact that institutions and individuals form "irrational" attachments to particular technologies for a variety of reasons; this may either reduce the chances of the "best" technical option surviving (since few are prepared to give it fair consideration) or alternatively keep it alive longer in the face of initially adverse circumstances.)

Another consequence of the influence of small events is that prediction of the outcome becomes very difficult. Naturally when the advantage of one technology is overwhelming this is not the case, but when no option is obviously superior increasing returns may secure total success for one at the expense of all others, rather than a splitting of the spoils in proportion to effectiveness. Increasing returns increase instability and decrease equilibrium, rendering forecasting a more hazardous process yet.

Technology policy, whether of the firm, industry or Government, must therefore take account of the problems of predicting the technological future and of the dangers of lock-in. Increasing returns are a potential enemy of both.

5. IMPLICATIONS

The problem of technological lock-in was examined in the last section of this chapter. The implications of the findings - that increasing returns mean that the competitive process can throw up a winning technology which does not lead to the eventual maximisation of economic efficiency - are very important, and go well beyond the realms of technology policy.

The first consequence is that a competitive system cannot be relied upon to produce the economically efficient outcome in every case. Traditional theory looks at the possible outcomes of choices, and 'optimises' between them to select the best. EMIR insists that a process of competition has to precede an outcome - it is not instantaneous. During the process, increasing returns may temporarily favour one 'competitor' (whether firm or technology) over the theoretically optimal contestant. Adam Smith's "hidden hand" gropes blindly, and may sometimes grasp the wrong solution.

Secondly, and following from this, there is a counter to the last defence of the Neoclassicals. When assailed by the empirically-based arguments that (for example) economic actors are never really in possession of all relevant information, that markets are never perfect, that the economy is never truly in equilibrium, they reply roughly as follows: "Of course, that is true in a purely literal sense. But is doesn't really matter, because the wonderful thing about the market is that it produces the same result 'as if' we did have perfect information, perfect competition and perfect equilibrium. Those who try out less than optimal solutions to economic problems will see that others do better by choosing better solutions- even if the choice is made by chance."

The fallacy of this argument in the presence of increasing returns has been proved quite clearly by EMIR for technological competition; it is not hard to see that the same argument applies to all other forms of competition. The 'as if' argument does not stand up, because it has been shown that competition does not always automatically select the optimal outcome. Therefore, the whole edifice must fall: markets are not perfect, actors not omniscient, economies not in equilibrium. Moreover, they do not have to behave in the long run 'as if' they were.

Chapter 11: Conclusion: Uncertainty and Increasing Returns

In this concluding chapter the arguments and results of the work will be summarised, and some implications will be highlighted. In the third part of this chapter the use of models for analysing complex problems such as scale and technology choice will be discussed. Finally, the fourth section ends with some criticisms of the work, and suggestions for further lines of enquiry.

1. SUMMARY

It will be useful to summarise the most important findings again under the three main headings of "Theory", "Policy" and "Decision Aids":

1.1 Theoretical Results

(i) In Chapter 2 it was shown that the conventional theory of scale economies was inconsistent, contradictory, and unsupported by the available empirical evidence.

(ii) In Chapter 3 the "dynamic diseconomies" of scale were demonstrated. "Static" construction-cost economies of scale were shown to be only one of the elements which determine the real costs of operation with plants of different sizes.

(iii) In Chapter 4 a new and original derivation of the principle of "technological heuristics" was produced. This argued that in an uncertain world we should expect to find that technical progress followed clearly-defined paths, which changed only rarely. In Chapter 5 these arguments were embodied in a computer model of progressive technical improvements. Simulation runs from this model yield convincing "learning curve" patterns of cost reduction.

(iv) Some highly contradictory ideas about optimal scale in several large-scale production industries were presented in Chapter 6. A theoretical argument, borrowed from the Grid-Group theory of Social Anthropology, demonstrates why this is to be expected. Conflicts of "opinion" about the optimum scale are inevitable.

(v) In Chapters 7 and 8 a new model of competition under increasing returns (EMIR) was described. This computer simulation model does not suffer from the theoretical problems outlined in Chapter 2, and pays close attention to the empirical research on the economics of production and technological change.

(vi) This new model was used in Chapter 9 to study the evolution of industry structure (production costs and firm and plant scale). Amongst other results derived from the experiments in Chapter 9, it was found that the presence of economies of scale does not by itself lead to concentration, and that greater scale economies do not necessarily lead to greater concentration. It was also demonstrated that industry structure need not be viewed as an arbitrary and exogenous factor, but that it can be seen evolving as a result of the competitive pressures within the market.

(vii) In Chapter 10 the model was used to show how "Technological Lock-in" occurs. This is particularly interesting as a theoretical development, because it is a good exmaple of a problem in the economics of technology, scale and increasing returns which is not addressed by existing models.

1.2 Results for the Policy Analyst

The policy analyst is primarily concerned with the issues of economic efficiency: what has to be done to ensure that the industry as a whole prospers and achieves the best possible costs and technologies?

(i) The survey of empirical studies of scale economies in Chapter 2 showed that the largest firm sizes found in practice are not a necessary consequence of the existence of production (or any other) scale economies. Calculated "minimum efficient sizes" for plants are often much smaller than the output of such firms; thus their size is not apparently necessary in the interest of economic efficiency. There are cases where there is confusion, doubt or dispute about the actual level of the m.e.s.

(ii) The simple simulation model of Chapter 3 shows that systems based on small-scale, flexible technology have better error-handling characteristics. That is, mistakes are less likely to be made, and can be more quickly corrected, with small, low lead-time production units than with large, long lead-time plants.

(iii) Chapter 5 (illustrating the theoretical arguments of Chapter 4) showed how the capability of successive process plants can exhibit cumulative learning effects (like the "learning curve" in cumulative output of goods from a single plant).

(iv) In Chapter 6 it was argued that people's positions in debates about scale are shaped by cultural biases which help (or make) them see things in particular ways. Thus it is possible to find examples of industries where there is deep disagreement about apparently purely "technical" questions.

(v) Chapter 9 produced several results concerning the determinants of industry concentration. Surprisingly, in view of conventional theory (but not inconsistently with the existing empirical research), it was found that there are circumstances in which lower scale economies produce higher degrees of industry concentration. It was shown that market share was the crucial factor for competitive success in EMIR. It was also found that over-competitive industries were less profitable, even for the most successful firms. Concentration was associated with past levels of competitiveness; large firms were present in an industry because they had succeeded in the past.

(vi) In Chapter 10 EMIR was used to model the problem of Technological Lock-in. The results show that purely market-based, competitive selection mechanisms cannot be relied upon to select the "best" technology in the long run.

1.3 Results for the Decision-Maker

The individual decision-maker is concerned with optimising the performance of a single firm. The perspective adopted in many of the models, particularly in EMIR, might encourage a certain fatalism about the possibility of aiding decisions about scale under increasing returns. However, a number of useful insights have been gained, and these include:

(i) The simulation of dynamic diseconomies of scale in Chapter 3 show that small scale flexibility can be worth more than even substantial static large scale economies under conditions of uncertain future demand.

(ii) A new plant is an opportunity to learn and innovate. Chapter 5 showed how process change can yield cumulative learning effects; a change in scale often implies a change in technology, and vice-versa.

(iii) The EMIR results of Chapter 9 show very clearly that gaining market share is a more important indicator of long-term competitive advantage than short-term profitability. That is, it is worth making long-term investments in pre-emptive capacity additions to gain ground on rivals. The other side of this coin is that, once it becomes clear that you are not going to "win" in an industry, it may be preferable to withdraw rather than to compete too hard; it was seen that highly competitive industries become can unprofitable, even for the winners.

(iv) Technological "Lock-in", as demonstrated in Chapter 10, is a serious problem for the individual economic actor. Moreover, the problem can be generalised to any question of choice under increasing returns. There is no easy way out of this difficulty; it is very important to be aware of its existence.

2. DISCUSSION

In this section I will expand on some of the points summarised above, and develop a context for them. There is a consistent theme running through much of the thesis, and it has to do with the problem of "uncertainty":

2.1 First Principles

To go back to the beginning for a moment: when discussing the problem of scale with people, it quickly becomes clear that, to many, scale seems not such a difficult thing to deal with. Two arguments are often found to be common to those with such attitudes. Firstly, whilst wrong decisions may have been made about scale in the past, sometimes big mistakes, really these were due to inadequate "technique". That is, more information, of better quality, analysed and processed in better ways, would have averted the errors of the past. Better forecasts of future demand and of the actual costs of constructing and running large plants would remove the problems. Secondly, it is taken as virtually self-evident that larger is better. For if that were not the case, how could the larger organisations and the giant production units survive in such a competitive world?

These two "common sense" reactions to the problem of scale - that a bit more information will make the problem go away, and that what is must necessarily be the most efficient because of its very existence - are in fact extremely common. They appear almost axiomatic in traditional ways of looking at scale. One of the chief of these is NeoClassical microeconomic theory.

2.2 Economic Theory

Economic theory reduces the problem of scale to the task of locating the lowest point on a "U-shaped" cost curve. That is, engineers, accountants and managers will be able to compare directly the total costs of production at different scales of plant, decide which is cheapest, and act accordingly. If they are not able to do this immediately, then finding optimum scale is only a problem of technique; enough research and information collection will eventually settle the question. In any event, the workings of the economy will provide a good approximation to the answer, for inefficient producers will inevitably be driven out of existence. Thus the extant plants and firms in a mature industry are unlikely to be far from optimal scale (given the technology they employ).

This seems plausible, but closer examination has revealed some serious problems with the economic theory (which have some far-reaching consequences).

The difficulties originally arose from the admirable objective of producing a watertight and consistent model of the behaviour of the market - how is it that a stable price emerges from all the interactions of producers and consumers? A mathematical description was devised some fifty years ago positing an equilbrium relationship between supply and demand. In order to do this, it was necessary to assume that costs of production were not affected by changes in the scale of output. Another, better-hidden, assumption was that there was no change in scale of production for changes in productive technology. Basically it was necessary to do away (temporarily, it was thought at the time) with all kinds of increasing returns to scale. If there are increasing returns then a simple equilibrium will be unstable, for as a firm gets bigger it will become more economically efficient and therefore it will tend to get even bigger still, until one economic actor comes to dominate each market.

This theory was a considerable intellectual achievement. It was acknowledged that the assumptions were unrealistic, but it was confidently believed that the scaffolding provided by these simplifications could be removed in due course. Meanwhile, the description of the economic effects of scale was left in a situation where there were allowed to be no real economic effects of scale at all. The long run cost curve had to ignore changes in technology and changes in factor input proportions, whilst empirical research has repeatedly shown that these are the very sources of reduction in production costs.

Worse was to come. Theorists had simply assumed the existence of U-shaped cost curves, i.e. that there is some optimal scale for production size (whether plants or firms). Empirical measurements to test the theory were at first extremely crude and unreliable, fitting unrealistically simple production functions to heterogenous data sets and coming up with conflicting results. As methodologies have become more sensitive, the work of the econometricians has tended to demonstrate firstly that, in general, economies of scale tend to extend over the whole range of firm and plant sizes, and secondly that there is still a considerable degree of difficulty in establishing both the sources of the economies of scale and their magnitudes. Occasional "pathological" cases have been found of cost curves with several minima. A more exhaustive review of the theory and empirical studies than any yet published was presented in Chapter 2. It was shown that even in the case of the mostly deeply researched industry (electricity generation) there is room for considerable dispute over the technological and economic "facts" of the case. (Very recent developments in the UK, where a quarter of a century of offical statements about the true economics of nuclear electricity have been placed in serious doubt, serve to underline this argument.)

The economic theory of scale presents a sorry spectacle. In many areas the empirical facts are still subject to considerable debate. The best-established finding, that in most industries there is no necessary maximum economic scale of operations, spells doom for the traditional microeconomic model of the market. Increasing returns of any kinds, in fact (including returns to technological change) present serious problems. There is therefore no good existing explanation of how firms come to be of a particular size, only vague assertions about the difficulty of managing large units. These assertions are not, however, well-substantiated either by the economics literature or by the labours of organisation theorists.

Thus it turns out that, far from a little more information being required, over fifty years of investigation and improvement of econometric technique has not so far managed to equip us with definite answers to even general questions about economies of scale. Moreover, given that economies of scale seem to exist, and that U-shaped cost curves tend to be exceptions more often than rules, there is no real explanation of how firms and plants come to be the sizes they are. No explanation, that is, which is based upon economic necessity alone.

2.3 Uncertainty and Contradictory Certainties

Even supposing that the existence of economies of scale in constructing large capital equipment is unproblematical, there are further complications. The electricity supply industry was used as a case to illustrate the complexities involved in assessing "static" economies of scale, but there are additional dynamic factors to be considered. The simple simulation model of Chapter 3 shows that influences from the outside world can dramatically affect the cost-minimisation problem even where the existence of the static scale economies are taken as given. In certain scenarios it becomes more efficient to construct smaller production units, even though these are apparently more expensive per unit of installed capacity. The problem lies in the uncertainty of future demand and the need to anticipate it.

(It can be noted in passing that the conceptually simple model of Chapter 3 throws light upon diseconomies of scale which traditional theory, the "Single Vision" of the Analytics, does not even mention. This is another illustration of the merits of a dynamic approach to such problems.)

The problem of scale is hedged around with uncertainties and disputes at the theoretical level. This might appear to be mere academic quibbling; perhaps the economists may not have a strong case, but surely the practical people, the engineers and managers, must know the truth of the matter? When we look at the opinions of some practitioners in industry, however, and compare their views with those of other experts (both "insiders" and "outsiders") we see that the theoretical uncertainties and disputes are not necessarily resolved: there are indeed "contradictory certainties" proposed by figures within some traditionally very large-scale, capital intensive production industries (e.g. paper manufacture, cement, electricity generation and brewing). In

Chapter 6 evidence was advanced to suggest that managers sometimes adopt "myths" of scale - convictions about the optimum size which are not always justified by the available evidence.

It has begun to look as if the search for "a bit more information" is rather futile, at least in some circumstances. One way out of the impasse is to avoid deciding which of the contradictory certainties is correct, for that is a question which seems to become more difficult to answer the deeper one investigates. It may be more fruitful to consider what assumptions are necessary in order to justify each of the conflicting views about scale. Into what worldview does the presence of economies of scale most naturally fit? Why do people wish to believe that small is beautiful?

The "grid-group" theory from social anthropology provides a context for examining these questions. A typology has been suggested which seems to make sense of some aspects of the debates about scale (and other issues) which are not addressed by the usual kinds of arguments about "rational" behaviour. There may be some ultimate truth about scale, but it is very hard to reach. Understanding of many such policy debates will be helped not by asserting that one or other solution must be right, but by considering in what kind of world and for whom each proposed answer is relevant. This way of looking at "reality" as being socially constructed carries with it not only the possibility that there will be contradictory views about what the "optimum" scale is, but a virtual guarantee that there will be irreconcilable convictions.

2.4 Technical Change: Systematic Behaviour in an Uncertain World

The issues of technical change and innovation are important problems which are closely linked to the problem of scale. Traditional microeconomic theory assumes away the question: all economic actors are supposed to have perfect, instant and equal access to all technological information. Technical change, when it occurs at all in this framework, has to be seen as a basically arbitrary event in which the Promethean fire of innovation strikes like lightning; apparently at random and never in the same place twice.

I have developed a different approach in Chapter 4, assuming that we live in an uncertain world in which the outcome of any particular action can never be predicted exactly. The example of scale economies shows that there can be a quite a high degree of uncertainty associated even with hard and apparently well-behaved objects like production machinery. This being the case, some predictions can be derived for the kinds of ways in which the development of a technology should progress: generally incrementally, and governed by rules which define the parameters within which engineers and technologists operate. Far from being arbitrary, technological progress can be expected to be generally quite systematic.

The existence of technological "guideposts", "trajectories" or "paradigms" has been posited by researchers in this area who have borrowed concepts from the philosophy and sociology of science. The derivation employed in Chapter 4 is different and original.

The argument rests upon the "Uncertainty Principle": that, in the face of complex problems it will often be more effective to deliberately restrict the set of possible actions. In the case of the cultural theory this leads to stable configurations of social relationships, values and "worldviews". In the instance of technological heuristics it means that particular "technological trajectories" will be followed by intending innovators. In both cases the complexity or "scale" of the problem demands that some kinds of cognitive filters have to be consciously or unconsciously donned to make sense out of uncertainty.

The result of the sections on technical change, illustrated by the model of Chapter 5, is that we can argue that

(a) there are systematic, rule-governed elements in the process of technological innovation;

(b) there are also random elements, in the sense that the outcome of a technological experiment is never guaranteed, always containing some element of uncertainty;

(c) scale change and technical innovation are closely linked (as implied from the survey of the economics literature).

(d) technical change is a cumulative process.

2.5 The Return of Increasing Returns

A continuing theme has been the contention that economics requires dynamic models to truly represent certain aspects of the economic process. This is not merely because of the extra detail which a dynamic model would add to the economic analysis. It is because the economic phenomena are themselves dynamic and changing; the move from economic statics to economic dynamics involves a qualitative transition, and not merely the addition of some extra complications to essentially the same model. Producing a good economic model is like learning to ride a bicycle: the nature of the task means that it is much easier to stay upright while the thing is moving, and very much more difficult to do it the other way round (trying to balance in stationary equilibrium and then move off when that problem has been mastered).

The most important element left out of the static economic model of scale choice is increasing returns. (There are said to be "increasing returns" when the marginal benefits of some factor increase as that factor is employed at a larger scale; the benefits increase at an increasing rate.) Economies of scale are one source of increasing returns, and cumulative technical change and improvement another. Use of the "Uncertainty Principle" allows us to see the technical change process as internal to the economic system, rather than as external and arbitrary; given this advantage it should now be possible to attempt a new economic description.

Taking into account some well-established stylised facts about both economies of scale and technical change, and assuming that firms are faced with an uncertain environment and so have to forecast, the model EMIR has been produced. A time-dependent model of oligopolistic competition emerges when a computer program is substituted for a set of equations. The novelty of EMIR lies in: its introduction of economies of scale; its sophisticated and endogenously-generated model of technical change; and its incorporation of plural rationalities.

The first, and perhaps most surprising, conclusion from the EMIR model is that purely static economies of scale are not nearly so important as we would have expected. The general tendency in every case where significant increasing returns (economies of scale and technical change) were available is for industrial concentration to increase over time, and to increase more rapidly the greater the magnitude of the "increased returns". (In a sense the model proves the equilibrium theorists correct, for it shows that increasing returns do lead to eventual concentration of the industry.) In a number of cases the result of a simulation run is that a single actor (firm) is left as the victor of the economic competition. However, those simulation runs in which there are high capital costs, and hence relatively greater "static" economies of scale, lead to lower levels of concentration and competition. The interpretation of this is that industries in which it is more difficult to add large chunks of capacity (because of high initial costs) are less competitive; it takes longer for a firm or group of firms to achieve a significant advantage through either scale of production or superior production technology. This may explain why attempts to link industry structure to measurements of (static) economies of scale (Scherer et al 1975) have not been markedly successful.

Secondly, it is found that competitive success does not necessarily, or even generally, lead to higher profits during the simulation runs. That is, there are technology/industry/strategy configurations which produce more competitive regimes, with more firms being driven out of business and fewer surviving to dominate the market. The victors of this corporate warfare do not tend to show higher absolute levels of profits than the most successful firms in less stressful environments. Thus "survival of the fittest" can be seen to have different aspects: aggression does not necessarily lead to prosperity. A less competitive regime may produce more survivors, with greater individual wealth than the winner of the more competitive regime.

The third main finding was discussed in Chapter 10. The detailed modelling of technology and innovation permits the competitive development of technologies to be simulated. EMIR very clearly shows how "technological lock-in" is an important fact of economic life. Again it is a strong example of path-dependence in economic processes - global optimisation might favour one technological variant over another, but if the early history does not favour the "optimal" technology, it may never get the chance to establish itself. We cannot rely on competition alone to select the best of a set of different technologies.

This last point is crucial, and the argument can of course be extended from technologies to policy choices in general; the statement that "What is, is best, and has become so because it is best" is not true. In particular, it should not be argued (although, as we saw in the survey of economic theories of scale, it has been) that large firms and large production units have emerged because they are more efficient. This may be the case, of course; however their simple existence does not of itself prove it.

My thesis, then, is that the two common-sense propositions with which this chapter began are untenable. The facts simply do not support the view that optimal scale can always be selected by getting marginally improved information or better "technique", and the existence of increasing returns negates the argument that whatever is most successful at the moment is necessarily the optimum choice.

2.6 The Policy Dilemna

This concludes the discussion of the thesis. Where does this leave us? Essentially, with a dilemna, which I will outline here but not (unfortunately) be able to resolve. This "loose end" constitutes a whole new area of investigation in itself, but is worth setting out because of its importance to the issues raised above.

The argument as developed has been in some respects negative. The economic evidence on the beneficial effects of scale has been shown to be at best inconclusive. The existence of large scale does not demonstrate that "Big is Best", because (a) the traditional economic data do not support this conclusion when they are carefully examined, (b) there are areas of considerable controversy about the true nature of "the facts" anyway, and (c) more generally, the path-dependent nature of economic processes means that competition only brings about locally optimal states rather than global optima, as demonstrated by the EMIR. Furthermore, even if "the facts" are true, there are cases where they overlook other influences (e.g. the dynamic diseconomies of scale) which negate their importance.

How, then, faced with all these negatives and uncertainties, can we proceed? There always seem to be at least two views about what it "the right scale". Plural rationalities says there will always be at least two views, so allowing one rationality to choose will not necessarily be either efficient or popular. Witness the continuing debate about nuclear power for electricity generation in the UK; the fact that this debate is not just about scale makes the argument even more bitter. On the other hand, where there are increasing returns (economies of scale, technological progress) competition cannot be relied upon to produce the right answer.

Using the language of the cultural theory we can say that there are difficulties with all of the solutions likely to be proposed by the different rationalities. The Hierarchists and Sectists will wish to impose their own solutions - the former to preserve the existing order and cohesion of the hierarchy (e.g. the CEGB's strong organisational commitment to large-scale nuclear energy), and the latter in order to bring about a more just and safe world (as they see it, e.g. the Green opposition to nuclear power on environmental and other political grounds). The pragmatic rationality of the Entrepreneur proposes that the market will automatically sort out the disputes; the "hidden hand" will make the best possible choice. But when, say, nuclear technology gets a foothold, the infrastructural commitments alone, such as fuel production and waste recycling, may consume so many resources that alternative technologies (e.g. wind and wave power) are either not tried or are deprived of resources. (The infrastructural requirements are another source of increasing returns to adoption of a technology - see Arthur (1987).)

The dilemna is that no single decision-maker can be relied upon to find the best solution to the scale-technology-policy question, yet neither can the "hidden hand" of competition necessarily deliver the optimum either. The problem lies in the fact that , where there are increasing returns, one option may be "lucky" early on, or may have purely temporary or short-term advantages, so that it gains an early superiority. Increasing returns then mean that other, possibly better, solutions may never become sufficiently well-established that a realistic comparison of their relative merits ever becomes possible. Through increasing returns, plurality becomes a singularity as one option comes to dominate the whole economic system.

(The process by which plurality becomes singularity, and by which the different views of the world come into contact with "how the world really is", have been investigated in another simulation model which I call "The Surprise Game" - see Thompson and Tayler (1986).)

Thus, despite the theoretical developments, and the advice for the decision-maker which can be given as a result of this work, the problem for the policy analyst is in some ways even more difficult than before. Not only is the "best" scale not known, but it seems to have become a much less well-defined thing. Technique alone will not solve this problem; a solution must take into account both plural rationality and increasing returns.

3. PLURAL RATIONALITIES AND PLURAL MODELS

The prescription, therefore, is not that "Small is Beautiful" (or "Big is Best"). It is that we must guard against being dominated by a single large scale influence, whether that influence is embodied in a firm, a production unit, a single technology, or a single view of the world. Efficiency may seem to be served best by singularity, but long-term survival demands plurality.

I will conclude briefly on how this principle relates to the modelling and analysis of these kinds of problems.

The questions addressed here have been by any standards large and complex in themselves. It would be difficult to produce a single all-encompassing model to illustrate all of the factors at work, and it would probably be foolish to try. The approach has been to use simple models to illustrate particular aspects. The simulation of dynamic diseconomies of scale only looks at capacity, forecasting and utilisation problems. Another model examined technological learning in process engineering. Yet another simple argument was the use of the Uncertainty Principle to derive some conclusions about the likely nature of technical change.

There is always a risk of trivialising the subject matter by doing this, or indeed of falling into a naive reductionism. But the alternative is to set up some giant all-encompassing model which will explain everything, and the danger is that this giant single model will become like the monoculture which presents such potential dangers of sub-optimising in the economic and technological worlds.

Theories about the world, or about scale economies, can be thought of as enjoying increasing returns to adoption: the more people adopt a particular view the more likely others are to be swayed by it. In this way orthodoxy becomes established as a cultural trajectory, just as particular technological trajectories become established; this is essentially the Kuhnian view of science.

A strong illustration of this danger is provided by the case of the IIASA Energy Model. Several hundred person-years of effort were devoted to the construction of a simulation model which would predict the energy requirements and energy usage of the whole world for the next century. The model was for a while one of the most significant achievements of the International Institute for Applied Systems Analysis. But a few people had doubts about it, and a debate started behind the scenes. Finally, the truth came out: the model had done no more than capture a particular set of assumptions about the world, and its conclusions were almost completely specified by the initial assumptions which were put into it. The whole story came to light in a special issue of "Policy Sciences" (Keepin 1984, Thompson 1984 and Wynne 1984). It is now quite generally accepted that the critics were correct, and that the model was seriously flawed if it was intended to be more than a manifesto for one particular vision of the future.

The systems movement, and the systems approach to problems, has been criticised by some as basically a technocratic attempt to treat society as if it were a machine (Lilienfeld 1978). The IIASA case lends some support to this view. I believe that this need not be the case, so long as we are aware of the dangers of single vision. The need for plurality is just as strong in the modelling process as it is in all of the economic and technological processes which are involved in problems of scale. The kinds of relatively small models used here each give a partial account of how the relevant systems behave. The argument of this chapter is that, since only partial accounts are ever possible, we had better take account of this fact right from the start and proceed accordingly.

From the outset I have dealt more with the questions of pre-analysis; that is, with the inputs to the process of analysis from which scale decisions emerge. No answer has been given to the question "What is the best size?". The essence of the approach used here is that it pays to be sceptical towards answers and to question carefully the assumptions - or worldviews - which lie behind them. What we have to do is to allow the policy debate on scale, whether it is within the upper echelons of commercial or public organisations, or in the wider ranges of society, to be conducted in a way which recognises the need for plural solutions. To assist this process, it is necessary to have a plurality of views and models to ensure the robustness of the ultimate choices which will have to be made between the inevitably differing views of how the world is. As Blake put it:

> Now I a fourfold vision see,
> And a fourfold vision is given to me;
> 'Tis fourfold in my supreme delight
> And threefold in soft Beulah's night
> And twofold Always. May God us keep
> From Single vision and Newton's sleep!

4. CRITICISMS AND AREAS FOR FUTURE WORK

4.1 Criticisms

Some limitations of the work done, particularly of the restrictive assumptions embodied in the various models described, have been mentioned at different stages.

The simulation model of dynamic diseconomies of scale (Chapter 3) claims some strong conclusions. However it must be stressed that this model only looks at the situation where one single company is meeting the demand for the whole market. It is not competitive; an exploration of dynamic diseconomies where there is also competition would require an amended version of EMIR (for example). Thus the model of Chapter 3 represents the situation of a monopoly supplier (e.g. a utility company) rather than that of an atomistic grabber of market share.

The major output of the work described in the thesis is EMIR, the dynamic model of technology and scale change. A problem, with hindsight, is that EMIR was made too complex - there were simply too many elements of the model which could be varied, despite the simplifications made when the model was specified. This became clear as the results were written up for Chapter 9; a great deal had to be placed in Appendices, and yet the experiments described ignored a whole range of questions. For example:

- only a limited set of parameter choices was explored;
- radical technical innovations were not used at all;
- changes in worldview were barred.

Many of the more interesting results and predictions obtained with the model might have been found without introducing the extra complication of multiple worldviews and different strategies.

Design of experiments, analysis of results and their written exposition would all have been easier with a less complicated model.

4.2 Further Research

A corollary to this is that several avenues remain unexplored. The major purpose has been to show that this kind of model is capable of producing interesting and useful results, and some further areas for investigation were mentioned at the end of Chapter 9.

Clearly the demand series used in the EMIR experiment can be altered, and it has been suggested that, since plant sizes do not appear to be strongly influenced by the other experimental factors investigated so far, they may be a direct function of the size of the market. This would give interesting confirmation of the "proportional growth" hypothesis, which suggests that there is in many industries a consistent link between market and plant scale. (See Chapter 2 for details and references to the literature.)

Innovation in EMIR has been restricted to incremental changes only. Radical innovations are intrinsically more interesting (although more difficult to generalise about). Their effects in EMIR were briefly discussed in Chapter 7; further investigations would allow a study of the technical aspects of the Product Life Cycle to be carried out. This could be made much more useful if the EMIR were extended even further to include product- as well as process-innovations. This extension would require the demand "curve" to be replaced by a more complex relationship between the producer and "consumer", reflecting preferences between different "attributes" of different possible products.

4.3 Apologia

In conclusion, it could be argued (with some justice) that not merely the model EMIR, but the whole project of this thesis, is over-ambitious. It attempts to demolish the foundations of a long-established body of work, and quite clearly there is not space in a PhD thesis to put anything sufficiently substantial in their place.

To this criticism I would cheerfully plead guilty, but in mitigation argue that I believe I have provided a sketch of how an alternative foundation could be constructed. My case is that such redevelopment is long-overdue. When the new edifice has been raised, I am confident that it will include many of the elements I have dealt with here; an appreciation of increasing returns, an acknowledgement of bounded rationality (and perhaps of plural rationality as well), a realistic model of technological change, and a dynamic representation of economic processes.

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Appendix 3A: Dynamic Diseconomies Simulation Demand Series

	Name of Demand Series		
time	RED1	BLUE2	BLUE5
2	14	31	21
3	2	62	43
4	4	92	66
5	19	121	90
6	45	149	115
7	82	177	141
8	130	205	167
9	186	233	195
10	250	260	223
11	322	288	252
12	400	315	282
13	484	342	312
14	574	370	343
15	668	398	375
16	765	426	407
17	866	454	440
18	970	483	473
19	1076	512	507
20	1183	541	541
21	1291	571	576
22	1400	602	611
23	1509	633	647
24	1618	664	683
25	1726	696	719
26	1833	729	756
27	1939	763	793
28	2043	797	830
29	2145	831	867
30	2244	867	904
31	2342	903	942
32	2436	940	979
33	2527	977	1017
34	2615	1016	1055
35	2700	1055	1092
36	2781	1094	1130
37	2859	1135	1168
38	2932	1176	1205
39	3002	1218	1243
40	3068	1260	1280
41	3130	1304	1317
42	3188	1347	1354
43	3241	1392	1391
44	3291	1438	1428
45	3336	1484	1464
46	3377	1530	1500
47	3414	1578	1536
48	3447	1626	1571
49	3476	1675	1606
50	3501	1724	1641
51	3523	1774	1675
52	3540	1825	1709
53	3553	1876	1742

time	RED1	BLUE2	BLUE5
54	3563	1929	1775
55	3569	1981	1808
56	3572	2035	1840
57	3572	2089	1871
58	3568	2143	1902
59	3562	2199	1932
60	3552	2255	1962
61	3540	2312	1991
62	3525	2369	2020
63	3508	2427	2048
64	3488	2486	2076
65	3466	2546	2103
66	3443	2606	2129
67	3417	2667	2154
68	3390	2729	2179
69	3362	2792	2204
70	3332	2855	2227
71	3301	2920	2250
72	3269	2985	2272
73	3237	3052	2294
74	3204	3120	2315
75	3170	3188	2335
76	3137	3258	2355
77	3103	3329	2374
78	3069	3401	2392
79	3036	3475	2410
80	3003	3550	2427
81	2970	3626	2443
82	2938	3704	2459
83	2907	3784	2474
84	2877	3865	2488
85	2847	3949	2502
86	2819	4034	2516
87	2792	4121	2528
88	2767	4210	2541
89	2742	4302	2552
90	2720	4396	2563
91	2698	4493	2574
92	2679	4592	2584
93	2661	4694	2594
94	2644	4799	2603
95	2629	4907	2612
96	2616	5018	2620
97	2605	5133	2629
98	2595	5252	2636
99	2586	5374	2644
100	2579	5500	2651
101	2573	5630	2658
102	2569	5765	2665
103	2565	5905	2672
104	2563	–	–
105	2562	–	–
106	2561	–	–
107	2561	–	–
108	2561	–	–
109	2561	–	–
110	2560	–	–

time	RED1	BLUE2	BLUE5
111	2560	-	-
112	2558	-	-
113	2556	-	-
114	2551	-	-
115	2545	-	-
116	2537	-	-
117	2526	-	-
118	2513	-	-
119	2495	-	-
120	2473	-	-
121	2447	-	-

Appendix 3B: Structure of Model Used in Simulation of Dynamic Diseconomies of Scale (Chapter 3)

The model involves the single firm or actor forecasting future demand. To meet this expected demand the firm builds production units, which have lead times which increase with their scale. The financial performance of the firm depends upon the utilisation of the units it builds, and upon the costs of adding capacity. Bigger units costs less to construct, because of capital scale economies.

PRODUCTION UNITS

Production units have three characteristics: size, lead time and cost.

Scale (output per period)	Lead Time (periods)	Construction cost per unit of output
100	24	380
200	27	329
400	33	284
900	45	240
1500	54	215

Note: one period is intended to correspond to one month. A 54-period lead time is thus 4½ years, which is representative of a large electricity generation plant (for example).

There is an additional effect upon capital costs besides the economies of scale. A 90% learning curve effect is embodied; this means that for each doubling of the number of units built, the costs of building a unit decreases by 10%. This figure is consistent with data for electricity generating units given by Kennedy and Allen (1979).

FORECASTING

The forecasting section of the program uses an exponentially weighted moving average, involving a two-parameter formulation of local linear growth. The parameters are the current estimates of the level of demand, m(t), and of the rate of growth of demand, b(t). The updating equations are:

$$m(t) = m(t-1) + b(t-1) + A1*e(t)$$

$$b(t) = b(t-1) + A2*e(t)$$

$$e(t) = y(t) - Y(t)$$

where

$y(t)$ = actual demand at time t

$Y(t)$ = forecast demand for time t made at t-1

The forecast for k time periods ahead is given by

$$Y(t,k) = m(t) + k*b(t)$$

The values of A1 and A2 may be varied to give different weightings to past data. For the purposes of this model the values used were

$$A1 = 0.3$$

$$A2 = 0.0267$$

The parameters are linked by the relations

$$A1 = 1 - w^2$$

$$A2 = (1 - w)^2$$

This defines Brown's Second Order method (Course notes on Forecasting, Warwick MSc MSOR). The value of w was chosen by trial-and-error from within a range of values which had proved appropriate in other forecasting applications.

The appropriateness of this forecasting method, and its effect upon the results, might be questioned. However, it must be remembered that the aim of the chapter is to compare the outcomes of employing units of different scales. The same forecasts apply, whatever the unit scale. Differences in results between different unit scales arise for two reasons. The first is the step-fitting performance, which is a function of unit size and little else. The second is construction lead time, which feeds into forecast error, as forecasts have to be made further into the future for longer lead time units. The increase in forecast error for longer lead times is a general effect, which does not depend upon the particular method employed or the exact choice of parameters.

FINANCIAL FACTORS

Financial results are affected by the relative importance of capital construction costs, income and other costs. The relationship could be loosely defined as "capital intensity", and is operationalised in the model as a ratio. This is done by setting, for each period,

Income = 15 * RATIO * MIN(capacity, demand)

Outgoings = Capital costs + 8 * RATIO * No. of units in operation

Capital cost = Total construction cost / lead time

That is, the user inputs a value for RATIO at the start of the simulation. Then income is received on all units for which there is demand, and costs on all units which are available (i.e. have been constructed). Capital costs are charged on units under construction, spread evenly over the construction lead time.

The firm's "bank balance" at period t is then given by

BANK(t) = BANK(t-1) + Income - Outgoings - Capital costs

Finally, interest is charged (or credited) on bank balances. The program assumes a period is one month; interest is calculated at 6%, 9% and 12% on positive bank balances, and at 9%, 12% and 15% on overdrafts. There are thus three financial reports at the end of the simulation, corresponding to three different interest rate assumptions.

Note that the bulk of the analysis in Chapter 3 concentrates upon capacity-demand fitting performance, and not upon financial outcomes. Financial outcomes are dependent upon the several parameters described in this section, whilst capacity fitting does not.

DECISION RULE - TO BUILD

The decision rule for constructing units is simple, and is based on a breakeven calculation.

The income generated for every unit of demand supplied is set by the model as 15 * (capital intensity RATIO). The fixed costs incurred in each time period are set at 8 * (capital intensity RATIO) * (unit scale). This means that the breakeven point is always

$$G = 8 * (\text{unit scale}) / 15$$

That is, if the predicted shortfall in suppply will be greater than G (according to the forecast), then an additional unit will make a profit if it is built, and so one is ordered.

DECISION RULE - TO RETIRE

The rule for retiring units is based on what actually happens at time t; there is no advantage to be gained from retiring units early, as the lead time for retiring units is zero. If supply exceeds demand by more than 3 * G then a unit is retired. It is important to note that only one unit may be retired in each time period, and that the interval 3 * G is arbitrary. The reason for these choices is that more sensitive decision rules for retiring units tended to give rise to "irrational" behaviour i.e. ordering new capacity and retiring units at the same time. This is because retiring is based on current demand, and building on expected future demand.

FAILURE PROBABILITIES

A feature of the model which is <u>not</u> used in these experiments is that plants may have a small chance of being unavailable due to failure. If this facility is used, then the model tests each unit for failure every period. The failure corresponds to downtime due to maintenance requirements, strikes, etc, and is an important feature of industries such as electricity supply. The failure probabilities may be constant, or a function of unit scale. (Again, this latter case would correspond with the electricity generation industry).

Unit failures were not modelled in Chapter 3 because they add extra complications; the analysis of Chapter 3 is presented for illustrative purposes, rather than as an exhaustive exploration of the model.

THE PROGRAM LISTINGS

The program code is provided as Appendix 3C. Note that there are two programs; the first creates a data file listing all units built and retired, whilst the second uses this file to run the simulation and perform the financial calculations. This split is because of the potential use of failure probabilities - several runs could be done using the same series of plant decisions, but with different random number streams for plant failures.

Previous versions of the program were arranged to report period-by-period the state of the simulation; this was used to assist in verifying the correct operation of the program. This output is suppressed in the listing provided.

Appendix 3A: Program Listing for Dynamic Diseconomies of Scale Simulation (Chapter 3)

The first program creates a data file which tells the second program what events (unit beinng built, unit retired, etc) occur during the simulation. The second program carries out the simulation and allocates costs.

```
10 '              Creates units and events files
20 INPUT "CODE OF UNITS TO BE CONSIDERED";K
30 OPEN "I",£1,"DATA9"
40 DIM M(120),B(120),D(5),DEM(200),P(220),E(120),UN(200)
50 IF K=1 THEN 110
60   FOR I=1 TO K-1'                     Input units data
70         FOR J=1 TO 5'                 - ignore first K-1 sets
80         INPUT £1,Z
90         NEXT J
100  NEXT I
110  FOR J=1 TO 5'                       Input data on type K (see line 20)
120  INPUT £1,D(J)
130  NEXT J
135 CLOSE £1
140 D(2)=D(2)*(1-D(5))'                  Effective capacity = capacity *
150 Q=D(4)'                                                   failure prob.
160 INPUT "WHICH DEMAND FILE";A$
180 OPEN "I",£1,A$
190 INPUT "WHAT WILL YOU CALL EVENTS FILE";E$
200 OPEN "O",£2,E$
210 INPUT "WHAT WILL YOU CALL UNITS FILE";U$
220 OPEN "O",£3,U$
230 PRINT £3,1
240 PRINT £3,K
250 PRINT £3,0
260 PRINT £3,1
261 Q=D(4)'                              Q = units construction lead time
262 INPUT "Forecast horizon";FH
270        FOR T=1 TO Q+1
280        INPUT £1,X
290        NEXT T
300 CLOSE £1
310 OPEN "I",£1,A$
320 INPUT £1,RN
330 X=FIX(X/D(2))+1'                     X now holds no. of units needed at
340 DIM U(X)'                            time t = Q+1
350 A1=.3
360 A2=.0268'                            Forecasting coefficents
370 INPUT "Starting slope";B(0)
380        FOR T=1 TO FH
390        P(T)=T*B(0)
400        NEXT T
410 A=RN-Q
```

```
420        FOR T=1 TO RN
430        INPUT £1,DEM(T)
440        E(T)=DEM(T)-M(T-1)-B(T-1)
450        M(T)=M(T-1)+B(T-1)+A1*E(T)
460        B(T)=B(T-1)+A2*E(T)
470        P(T+FH)=M(T)+FH*B(T)
480        NEXT T
490    FOR T=RN+1 TO 220
500    P(T)=P(RN)
510    NEXT T
520 CLOSE £1
530 GAP=8*D(2)/15'                 8/15ths of plant size is the demand
540 GAP1=D(2)-GAP'                 gap to be filled
550 PRINT "Please wait a while....."
555 N=0'                           N holds number of plants
560        FOR T=1 TO Q
570        G=DEM(T)-N*D(2)
580        IF G.gt.GAP THEN 590 ELSE 620
590        N=N+1
600        U(N)=T-1'               U(N) holds time unit number N must
610        GOTO 570'               be built by
620        NEXT T
630 PRINT £3,N
640        FOR I=1 TO N
650        PRINT £3,U(I)
660        UN(U(I))=UN(U(I))+1     UN(J) holds no. of units available
670        NEXT I'                 at time J
680 CLOSE £3
690 N=0:T=0
700 DIM S(RN,2)
710        FOR I=1 TO RN
720        N=N+UN(I)
730        Z=N
740             FOR J=1 TO Q
750             Z=Z+UN(J+I)
760             NEXT J
770        G=DEM(I+Q)-Z*D(2)
780        G1=DEM(I)-N*D(2)
790        IF G.gt.GAP AND I.1t.RN-Q THEN 820
800        IF -G1.gt.3*GAP1 THEN 960 ELSE 880
820        UN(I+Q)=UN(I+Q)+1
830        T=T+1
840        S(T,1)=I-1'             Time build must start
850        S(T,2)=1'               Code 1 = 'construct a unit'
860        Z=Z+1
870        GOTO 770
880        NEXT I
890 PRINT £2,T
900        FOR I=1 TO T
910        PRINT £2,S(I,1)
920        PRINT £2,S(I,2)
930        PRINT £2,1
940        NEXT I
950 GOTO 1010
960 N=N-1'                         Retires a unit
970 T=T+1
980 S(T,1)=I'                      Time retire made
990 S(T,2)=3'                      Code 3 = 'retire a unit'
1000 GOTO 880
```

```
1010 PRINT "Calculating capital costs"
1020 CLOSE £2
1030 DIM Z(3)
1040 '                    Calculates costs before start of simulation
1060 OPEN "I",£2,U$
1070 INPUT £2,N '                  NO USE
1080 INPUT £2,C '                  CODE OF UNITS
1090 INPUT £2,DUM          '       NO. OF UNITS
1180 INPUT £2,X
1190 IF X=0 THEN PRINT "NO units under construction":END
1200 IF X.ne.1 THEN PRINT "ERROR"
1210 INPUT £2,N
1220 DIM UT(N),I(3)
1230      FOR J=1 TO N
1240      INPUT £2,X
1250      UT(J)=D(4)-X
1260      NEXT J
1270 D(3)=D(3)/D(4)
1280      FOR I=D(4) TO 1 STEP -1
1290           FOR J=1 TO N
1300           IF UT(J).ge.I THEN L=L+1
1310           NEXT J
1320      SUM=L*D(3)
1330      L=0
1340           FOR J=1 TO 3
1350           Z(J)=Z(J)+SUM
1360           Z(J)=Z(J)*(1+.0025*J)'   Interest charges
1370           NEXT J
1410      NEXT I
1420 OT$=U$+".COS"
1430 OPEN "O",£3,OT$
1440      FOR I=1 TO 3
1450      PRINT £3,Z(I)
1460      NEXT I
1470 CLOSE
1480 CLEAR
1490 END
```

This is the main simulation program:

```
10 '    disc-driven version
20 '    ££££££££££££££££££££
30 '    £ SCALE SIMULATION £
40 '    ££££££££££££££££££££
50 B$="------------------------------------------------------------------------"
60 C$="'   Time Period £££                             Demand £££££££££       '"
70 D$="'   Unit         No.    Failures           Available  '  Under          '"
80 E$="'   type                                   capacity   '  Construction   '"
90 F$="'   ££££         ££       ££               £££££££    '    ££           '"
100 G$="'   Total       £££       ££               ££££££££   '    ££           '"
110 Z$="'                                                     '                 '"
120 H$="'   Income (profit on variable costs)                   £££££££££       '"
130 I$="'   Fixed Costs                                         £££££££££       '"
140 R$="'                                                       ---------       '"
150 J$="'                                                       £££££££££       '"
160 K$="'   Capital Expenditure                                 £££££££££       '"
170 L$="'   Net Change                                          £££££££££       '"
180 M$="'   Cost of Money         9%            12%             15%             '"
190 N$="'   Interest Credit   £££££££££     £££££££££     £££££££££             '"
```

```
200 W$="'     Interest Debit      £££££££££       £££££££££      £££££££££       '"
210 O$="'     Current Balance     £££££££££       £££££££££      £££££££££       '"
220 S$="'                          -------         -------        -------       '"
230 T$="'                                                                  =========   '"
240 FX$="'     Random Seed £££   Capital Intensity £.££      Run Length £££      '"
250 XT$="'     Demand unsatisfied ££££££££           Overcapacity ££££££££      '"
255 ZT$="'     Utilisation ££.£%                                                 '"
260 DIM DAT(10,5)
270 DIM COM$(4)
280 PRINT "Command file?"
290 INPUT CM$
300 OPEN "I",£2,CM$
310       FOR I=1 TO 4
320       INPUT £2,COM$(I)
330       NEXT I
340 INPUT £2,RATIO
350 INPUT £2, FIN$
360 INPUT £2,SZS
370 INPUT £2,SZS$
380 CLOSE £2
390 DF$=COM$(1)
400 OPEN "I",£1,DF$'           Input units data
410       FOR I=1 TO 10
420            FOR J=1 TO 5
430            INPUT £1, DAT(I,J)
440            NEXT J
450       NEXT I
460 GOTO 470
470 CLOSE £1
480 UF$=COM$(2)
490 OPEN "I",£3,UF$
500 INPUT £3,DIFF
510 DIM Q(DIFF),N(DIFF),CAP(DIFF),FAIL(DIFF),UNITDAT(DIFF,5)
520       FOR I=1 TO DIFF
530       INPUT £3,Q(I)
540            FOR J=1 TO 5
550            UNITDAT(I,J)=DAT(Q(I),J)
560            NEXT J
570       NEXT I
580 DS$=COM$(3)
590 OPEN "I",£2,DS$
600 INPUT £2,RN
610 X=RN'                         Length of simulation
620 DIM DEMAND(X),CAPACITY(X),OUTGO(X),INCOME(X),FORECAST(X)
630 DIM CAPEXP(X),BANK(3,X),CRED(3,X),DEB(3,X),S(3),OVER(X),UNDER(X)
640       FOR I=1 TO X
650       INPUT £2,DEMAND(I)
660       NEXT I
670 CLOSE £2
680       FOR I=1 TO RN
690       IF DEMAND(I).gt.DEM THEN DEM=DEMAND(I)
700       NEXT I
710 X=DEM
720 P=UNITDAT(1,2)
730 Q=UNITDAT(DIFF,2)
740 R=UNITDAT(1,5)
750 S=UNITDAT(DIFF,5)
760 Q1=INT(X/P+1+2.5*SQR(INT(X/P+1)*R*(1-R)))' (over-)estimates of max.
770 Q2=INT(X/Q+1+2.5*SQR(INT(X/Q+1)*S*(1-S)))' no. of units needed
```

```
780 IF Q1.gt.Q2 THEN N=Q1*2 ELSE N=Q2*2
790 DIM UNIT(N),BUILD(N,4),CONSTR(DIFF)
800       FOR I=1 TO DIFF
810       INPUT £3,N(I)
820       IF N(I)=0 THEN 870
830            FOR J=1 TO N(I)
840            UNIT(UNITS+1)=I
850            UNITS=UNITS+1
860            NEXT J
870       NEXT I
880 INPUT £3,A
890 IF A=0 THEN 1070
900 IF A.ne.1 THEN PRINT "We're in trouble here!"
910       FOR I=1 TO DIFF
920       INPUT £3,Q
930       CONSTR(I)=Q
940       IF Q=0 THEN 1060
950            FOR J=1 TO Q
960            INPUT £3,BUILD(CONSTR+1,2)
970            CONSTR=CONSTR+1
980            BUILD(CONSTR,4)=I
1000           P2=N(I)^(-.152) ' Construction cost learning curve
1010           IF UNITS=0 THEN PRINT "(Don't Worry!)"
1020           P=P2
1030           IF P.gt.1 THEN P=1
1040           BUILD(CONSTR,3)=UNITDAT(I,3)*P/UNITDAT(I,4)
1050           NEXT J
1060      NEXT I
1070 CLOSE £3
1080 EV$=COM$(4)
1090 OPEN "I",£1,EV$'                Input from the events file
1100 INPUT £1,E: DIM EVENT(E+1,3)
1110      FOR J=1 TO E
1120           FOR I=1 TO 3
1130           INPUT £1, EVENT(J,I)
1140           NEXT I
1150      NEXT J
1160 PRINT "Random number seed?"
1170 INPUT RAND
1180 RANDOMIZE(RAND)
1190 CLOSE £1
1200 EV=1
1210 T=0
1220 IF EVENT(EV,1)=0 THEN 2010
1229 '                     Beginning of main loop
1230 T=T+1
1240 IF T.gt.RN THEN 2580
1250 IF EVENT(EV,1)=T THEN GOTO 2010
1260      FOR I=1 TO DIFF
1270      CAP(I)=0
1280      FAIL(I)=0
1290      NEXT I
1299 '                     Test units for random failure
1300      FOR I=1 TO UNITS
1310      S=RND:IF S.gt.UNITDAT(UNIT(I),5) THEN CAP(UNIT(I))=1
          ELSE FAIL(UNIT(I))=1
1320      NEXT I
1329 '                     Decide what capacity available this period
1330      FOR I=1 TO DIFF
```

```
1340      CAPACITY(T)=CAPACITY(T)+CAP(I)*UNITDAT(I,2)
1350      NEXT I
1360 PRINT
1370 PRINT "At time period ";T;"available capacity=";CAPACITY(T)
1380 PRINT "Demand=";DEMAND(T)
1390 GAP=CAPACITY(T)-DEMAND(T)
1400 PRINT "Difference=";GAP
1410 IF GAP.gt.0 THEN Z=DEMAND(T) ELSE Z=CAPACITY(T)
1420 IF GAP.gt.0 THEN OVER(T)=GAP ELSE UNDER(T)=-GAP
1430 INCOME(T)=Z*RATIO*15                        'variable costs
1440      FOR I=1 TO DIFF
1450      OUTGO(T)=N(I)*8*RATIO*UNITDAT(I,2)*(1-UNITDAT(I,5))+OUTGO(T)
1460      NEXT I
1470      FOR I=1 TO CONSTR                      'capital charges
1480      IF BUILD(I,2)=.1t.T THEN GOSUB 2460
1490      IF BUILD(I,2).gt.T THEN CAPEXP(T)=CAPEXP(T)+BUILD(I,3)
1500      NEXT I
1510 SUM=INCOME(T)-OUTGO(T)-CAPEXP(T)
1520      FOR I=1 TO 3
1530      BANK(I,T)=BANK(I,T-1)+SUM
1540      IF BANK(I,T).gt.0 THEN S(I)=1 ELSE S(I)=-1
1550      IF S(I).gt.0 THEN CRED(I,T)=BANK(I,T)*(.0025+.0025*I) ELSE
          DEB(I,T)=-BANK(I,T)*(.005+.0025*I)
1560      BANK(I,T)=BANK(I,T)+CRED(I,T)-DEB(I,T)
1570      NEXT I
1579 '                  End of main loop - return to 1230
1580 GOTO 1230
2000 '
2009 '                  If EVENT has occurred, decide which
2010 A=EVENT(EV,2)
2020 QZ=EVENT(EV,3)
2030 EV=EV+1
2040 IF A=1 THEN GOSUB 2220
2050 IF A=2 THEN GOSUB 2090
2060 IF A=3 THEN GOSUB 2350
2070 IF T=0 THEN T=1
2080 GOTO 1250
2090 '                  Subroutine to cancel capacity
2100 S=0
2110      FOR J=1 TO CONSTR
2120      IF BUILD(J,1).gt.S AND BUILD(J,4)=QZ THEN S=J
2130      NEXT J
2140 CONSTR=CONSTR-1
2150 CONSTR(QZ)=CONSTR(QZ)-1
2160      FOR J=S TO CONSTR
2170           FOR K=1 TO 4
2180           BUILD(J,K)=BUILD(J+1,K)
2190           NEXT K
2200      NEXT J
2210 RETURN
2220 '                  Subroutine - order new plant
2230 CONSTR=CONSTR+1
2240 CONSTR(QZ)=CONSTR(QZ)+1
2250 BUILD(CONSTR,1)=T
2260 BUILD(CONSTR,2)=T+UNITDAT(QZ,4)
2270 BUILD(CONSTR,4)=QZ
2280 '                  Learning curve construction costs effect
2290 P2=N(QZ)^(-.152)
2300 IF N(QZ)=0 THEN PRINT "(Don't Worry!)"
```

```
2310 P=P2
2320 IF P.gt.1 THEN P=1
2330 BUILD(CONSTR,3)=P*UNITDAT(QZ,3)/UNITDAT(QZ,4)
2340 RETURN
2350 '                      Subroutine to retire units
2360 N(QZ)=N(QZ)-1
2370 UNITS=UNITS-1
2380      FOR J=1 TO UNITS+1
2390      IF UNIT(J)=QZ THEN 2420
2400      NEXT J
2410 PRINT "No such unit"
2420      FOR L=J TO UNITS
2430      UNIT(L)=UNIT(L+1)
2440      NEXT L
2450 RETURN
2459 '                      Subroutine - bring unit into service
2460 UNITS=UNITS+1
2470 X=BUILD(I,4)
2480 N(X)=N(X)+1
2490 UNIT(UNITS)=X
2500 CONSTR=CONSTR-1
2510 CONSTR(X)=CONSTR(X)-1
2520      FOR Z=I TO CONSTR
2530           FOR Y=1 TO 4
2540           BUILD(Z,Y)=BUILD(Z+1,Y)
2550           NEXT Y
2560      NEXT Z
2570 RETURN
2579 '                      Final analysis and results storage
2580 OPEN "O",£1,"PRINT"
2590 PRINT "Please wait a few moments while I do final summary!"
2600 PRINT £1,""
2610 PRINT £1,""
2620 PRINT £1,"Unit specifications file  ";DF$
2630 PRINT £1,"Numbers of units file     ";UF$
2640 PRINT £1,"Demand series file        ";DS$
2650 PRINT £1,"Events from file          ";EV$
2660 PRINT £1,B$
2670 PRINT £1,USING FX$;RAND;RATIO;RN
2680 PRINT £1,B$:PRINT £1,M$
2690 PRINT £1,USING O$;BANK(1,T-1);BANK(2,T-1);BANK(3,T-1)
2700 DIM CR(3),DB(3)
2710      FOR I=1 TO RN
2720      OT=OT+OUTGO(I)
2730      INN=INN+INCOME(I)
2740      CAP=CAP+CAPEXP(I)
2745      IF CAPACITY(I).gt.DEMAND(I) THEN X=1 ELSE X=CAPACITY(I)/DEMAND(I)
2747      UTIL=UTIL+X
2750      OV=OV+OVER(I)
2760      UN=UN+UNDER(I)
2770           FOR J=1 TO 3
2780           CR(J)=CR(J)+CRED(J,I)
2790           DB(J)=DB(J)+DEB(J,I)
2800           NEXT J
2810      NEXT I
2815 UTIL=UTIL*100/RN
2820 PRINT £1,USING N$;CR(1);CR(2);CR(3)
2830 PRINT £1,USING W$;DB(1);DB(2);DB(3)
2840 PRINT £1,B$
```

```
2850 PRINT £1,USING H$;INN
2860 PRINT £1,USING I$;OT
2870 PRINT £1,R$
2880 PRINT £1,USING J$;INN-OT
2890 PRINT £1,USING K$;CAP
2900 PRINT £1,R$
2910 PRINT £1,USING J$;INN-OT-CAP
2920 PRINT £1,T$
2930 PRINT £1,B$
2940 PRINT £1,USING XT$;UN;OV
2945 PRINT £1,USING ZT$;UTIL
2960 PRINT £1,B$
2970 CLOSE £1
2980 OPEN "I",£2,"PRINT"
2990 IF FIN$="S" THEN 3010
3000 IF FIN$="P" THEN 3040 ELSE 2970
3010 INPUT £2,A$
3020 PRINT A$
3030 IF EOF(2) THEN 3070 ELSE 3010
3040 INPUT £2,A$
3050 LPRINT A$
3060 IF EOF(2) THEN 3070 ELSE 3040
3070 CLOSE £2
3080 END
```

Appendix 5A: Program Listing for Technological Learning Simulation (Chapter 5)

```
10 '    ££££££££££££££££££££
20 '    ££  Meta learning ££
30 '    ££££££££££££££££££££
100 INPUT "New run or old (N/O)";A$
110 IF A$.ne."N" THEN 1000
120                                         'GENERATE NEW PARAMETERS
130 OPEN "O",£1,"DAT01.Q"
200 K1=50000 +50000 *RND                    'FURNACE
210 K2=400+200*RND
220 K3=2000+1000*RND
230 K4=7500+4500*RND
240 K5=500+200*RND
250 K6=85+30*RND
260 K7=1.6+.8*RND
270 K8=1.1+.6*RND
280 K9=.95+.1*RND
300 C1=600+1200*RND                         'COMPRESSOR
310 C2=30+30*RND
320 C3=12+12*RND
330 C4=1.5+RND
340 C5=200+400*RND
350 C6=9+6*RND
400 D1=400+800*RND                          'BLENDER
410 D2=40+30*RND
420 D3=2000+2000*RND
500 F1=10+5*RND                             'INJECTOR
510 F2=1000+2000*RND
520 F3=.8+.4*RND
600 G1=4000+4000*RND                        'DISTILLATION
610 G2=100+80*RND
620 G3=10+4*RND
630 G4=800+400*RND
700 H1=12000+12000*RND                      'EXHAUST
710 H2=300+200*RND
800 L1=2+RND                                'COSTS
810 L2=1500+1000*RND
900 WRITE £1,K1,K2,K3,K4,K5,K6,K7,K8,K9     'WRITE TO FILE
910 WRITE £1,C1,C2,C3,C4,C5,C6,D1,D2,D3,F1,F2,F3
920 WRITE £1,G1,G2,G3,G4,H1,H2,L1,L2
930 CLOSE £1
940 GOTO 2000

950 '           ------------------------------------

1000 OPEN "I",£2,"DAT01.Q"                  'INPUT PARAMETERS
1010 INPUT £2,K1,K2,K3,K4,K5,K6,K7,K8,K9
1020 INPUT £2,C1,C2,C3,C4,C5,C6,D1,D2,D3,F1,F2,F3
1030 INPUT £2,G1,G2,G3,G4,H1,H2,L1,L2
1040 CLOSE £2
```

```
2000                                            'SET UP DATA FORMAT
2010 A$="-----------------------------------------------------------------"
2020 B$="'                                                              '"
2030 C$="' Control type ±     ±                      Plant no. £££      '"
2040 D$="' Total output ££££££££                       Yield £££.£%     '"
2050 E$="' Operating Temp ££££             Operating pressure ££.££     '"
2060 F$="'             Vol  Thickness '  Flow% Pressure% Temp%    Cost  '"
2070 G$="' Furnace  ££££££     ££.££  '  £££.£   £££.£   £££.£  £££££££££ '"
2080 H$="' Blender     Coeff. £.££    '  £££.£                  £££££££££ '"
2090 I$="' Injector   Rate £££££££    '                  £££.£  £££££££££ '"
2100 J$="' Distllrs £ Length £££££££ '  £££.£            £££.£  £££££££££ '"
2110 K$="' Exhaust  Capacity £££££££ '  £££.£                   £££££££££ '"
2120 L$="' Comp. ££.££ Flow ££££££££ '  £££.£   £££.£           £££££££££ '"
2125 Q$="' Control unit                                         £££££££££ '"
2130 M$="'                            '                         --------- '"
2140 N$="' Electricity cost £££££££££        Capital cost    £££££££££££ '"
2150 O$="' Cap. cost/Unit   £££££££££        Av. LR Cost  ££££££££££     '"
2900              '-------------------------------

3000 INPUT "Furnace Volume";VOLUME                   'INPUT DATA
3010 INPUT "Thickness of walls";THICK:PRINT:IF THICK.lt.1 THEN 3009
3020 INPUT "Compressor pressure";COMPRESS
3030 INPUT "Compressor flowrate";FLOWCOMP:PRINT
3040 INPUT "Blender coefficient";BLEND
3050 INPUT "Blender flowrate";FLOWBLEND:PRINT
3060 INPUT "Control option 1/2/3: manual/auto/computer";CONTROL
3070 IF CONTROL=1 THEN 3080
3071 IF CONTROL=2 THEN 3080
3072 IF CONTROL=3 THEN 3080
3073 GOTO 3060
3080 PRINT
3090 INPUT "Injector rate";RATE:PRINT
3095 IF RATE.lt.2*VOLUME THEN PRINT "Too low ":GOTO 3090
3100 INPUT "Number of coolers";N
3110 INPUT "Length of each distiller";LENGTH:PRINT
3120 INPUT "Exhaust capacity";CAPACITY:PRINT
3130 INPUT "Do you wish to alter anything (Y/N)";Z$
3140 IF Z$="Y" THEN 3000
3150 CONTROLN=.9+.05*CONTROL
3160 PRINT:PRINT
3900              '-------------------------------

4000 FLOW=VOLUME                                     'OPERATING VARIABLES
4010 IF FLOW.gt.FLOWCOMP THEN FLOW=FLOWCOMP
4020 IF FLOW.gt.FLOWBLEND THEN FLOW=FLOWBLEND
4030 TEMP=1000*(1-F3*VOLUME/RATE)
4040 IF COMPRESS.gt.K7+K8*THICK THEN PRESSURE=K7+K8*THICK ELSE
     PRESSURE=COMPRESS
4050 IF TEMP.gt.K5+K6*THICK THEN TEMP=K5+K6*THICK
4100 A=G3+G4*N*LENGTH                                'OPTIMISE FLOW/TEMP
4110 B=1/SQR(N)
4111 F=FLOW
4112 T=TEMP
4120 X=TEMP*A/(1+B*TEMP)
4130 Y=FLOW*((A/FLOW)-1)/B
4140 IF X.gt.Y THEN FLOW=A/(1+B*TEMP) ELSE TEMP=((A/FLOW)-1)/B
4141 IF TEMP.gt.T THEN TEMP=T
4142 IF FLOW.gt.F THEN FLOW=F
4200 PURITY=(TEMP/1000)*(1-.5/PRESSURE)*CONTROLN*BLEND*K9
```

```
4210 FLU=FLOW*(1-PURITY)                                    'EXHAUST
4220 IF FLU.gt.CAPACITY THEN FLOW=FLOW*CAPACITY/FLU:GOTO 4210
4300 ELECTR=C5+C6*FLOW*PRESSURE
4310 OUTPUT=FLOW*PURITY
4900            '----------------------------------

5000 FURNCOST=K1+K2*THICK*VOLUME^.67+K3*THICK+K4*VOLUME^.67
5010 COMPCOST=C1+C2*COMPRESS^1.5+C3*FLOWCOMP+C4*COMPRESS*FLOWCOMP
5020 BLENDCOST=D1+D2*FLOWBLEND+D3/(1-BLEND)
5030 IF CONTROL=1 THEN CONTROLCOST=5000
5040 IF CONTROL=2 THEN CONTROLCOST=45000
5050 IF CONTROL=3 THEN CONTROLCOST=125000
5060 INJCOST=F1*RATE+F2
5070 DISTCOST=N*(G1+G2*LENGTH)
5080 EXHCOST=H1+H2*CAPACITY
5090 CAPCOST=FURNCOST+COMPCOST+BLENDCOST+CONTROLCOST+INJCOST+DISTCOST
     +EXHCOST
5100 UNCAPCOST=CAPCOST/OUTPUT
5110 RUNCOST=.1*CAPCOST+L1*ELECTR+FLOW*(1-PURITY)*L2
5120 AVCOST=RUNCOST/OUTPUT
5900            '----------------------------------

6000 IF CONTROL=1 THEN M=20                                 'OUTPUT TO PRINTER
6010 IF CONTROL=2 THEN M=50
6020 IF CONTROL=3 THEN M=1000
6030 Q=100/M
6100 LPRINT:LPRINT
6110 LPRINT A$
6120 INPUT "Which number plant is this ";Z
6130 IF CONTROL=1 THEN Z$="manual"
6140 IF CONTROL=2 THEN Z$="auto"
6150 IF CONTROL=3 THEN Z$="computer"
6160 LPRINT USING C$;Z$,Z
6170 LPRINT USING D$;OUTPUT;PURITY*100
6180 LPRINT USING E$;TEMP;PRESSURE
6190 LPRINT A$
6200 LPRINT F$
6210 LPRINT USING G$;VOLUME;THICK;Q*CINT(M*FLOW/VOLUME);Q*CINT(M*PRESSURE/
     (K7+K8*THICK));Q*CINT(M*TEMP/(K5+K6*THICK));FURNCOST
6220 LPRINT USING H$;BLEND;Q*CINT(M*FLOW/FLOWBLEND);BLENDCOST
6230 LPRINT USING I$;RATE;Q*CINT(M*TEMP/(1000*(1-F3*VOLUME/RATE)));INJCOST
6240 LPRINT USING J$;N;LENGTH;Q*CINT(FLOW*M*(1+B*TEMP)/A);Q*CINT(M*TEMP*B/
     ((A/FLOW)-1));DISTCOST
6250 LPRINT USING K$;CAPACITY;100*FLU/CAPACITY;EXHCOST
6260 LPRINT USING L$;COMPRESS;FLOWCOMP;Q*CINT(M*FLOW/FLOWCOMP);
     Q*CINT(M*PRESSURE/COMPRESS);COMPCOST
6265 LPRINT USING Q$;CONTROLCOST
6270 LPRINT M$
6280 LPRINT USING N$;ELECTR*L1;CAPCOST
6290 LPRINT A$
6300 LPRINT USING O$;UNCAPCOST;AVCOST
6310 LPRINT A$
6320 LPRINT:LPRINT
7000 INPUT "Build another unit (Y/N)";S$                       'TRY AGAIN?
7010 IF S$="Y" THEN 3000
7020 END
```

Appendix 8A: EMIR Program Listing

```
10 '*******************************************************************
20 '* Scale-Competition-Technical Change Simulation Version 3.2  Aug86 *
25 '* Forecasting added; price model                                   *
27 '* Improved decision rules; random order; perfect capacity info     *
28 '* Disc-driven; information storage       Plural rationalities      *
29 '* Improved technical change              (C) Paul Tayler 1986      *
30 '* Variable scale and innovation strategies                         *
35 '* Arrays reduced to run through MSBASIC interpreter 11/11/89       *
37 '* Final changes made 07/01/90                                      *
40 '*******************************************************************
94 '
95 '       *** Begin Section A ***    (see Appendix 8C for program
96 '                                   structure references)
97 '  First section reads in data file called _M32A.RUN, which
98 '  contains instructions to set up the run.
99 '
100 OPEN "I",£2,"_M32A.RUN"
120 LINE INPUT £2,HEADING$
130 PRINT:PRINT HEADING$:PRINT
140 INPUT £2,OUTFILE$
150 INPUT £2,PLANTOUT$
160 COMMENT$=HEADING$
170 INPUT £2,RSEED
180 RANDOMIZE RSEED
185 INPUT £2,GWVW
190 DIM COEF(4)
199 '
200 DEF FNPRK(PRK,X)=PRK*EXP(.7*LOG(X))
210 DEF FNPRL(PRL,X)=PRL*EXP(.4*LOG(X))
220 DEF FNPRV(PRV,X)=PRV*1
230 DEF FNINV(PRK,C)=10*INT(EXP((1/.7)*LOG(C/PRK))/10)
240 DEF FNTCOMP(X,K,L,V,WV)=FNPRV(V,X)+((FNPRK(K,X)*COEF(WV))+
    (1.1-COEF(WV))*FNPRL(L,X))/X
299 '
300 INPUT£2,DEMFIL$
310 OPEN "I",£1,DEMFIL$
320 INPUT £1,DDAY
330 DDAY15=DDAY+15
335 DDAY20=DDAY+22
340 DIM DEMAND(95),CAPACITY(95),FORECAST(95,4),M(95,4)
345 DIM E(95,4),B(95,4)
350 FOR I=1 TO DDAY
360 INPUT £1,DEMAND(I)
370 NEXT I
380 CLOSE £1
399 '
400 INPUT £2,FMNO
410 INPUT £2,PLNO
420 DIM PLANT(80,6),NAM$(16),FIRM(16,4),OWNER(16,80),LOSER(80)
430 DIM VALUE(80),PLANTNAME$(80),INTEREST(16),FINCOME(16)
440 DIM PLINCOME(80),PLNOS(16),FMROR(16),PLCOST(80,4)
450 DIM PLAVCOST(80,4),TMPAVCOST(80),MRK(80),ORDER(16)
460 DIM K(16,3),L(16,3),V(16,3),MAX(16,3),MIN(16,3)
470 DIM RK(16),RL(16),RV(16),RMAX(16),RMIN(16),LASTINNOV(16)
480 DIM RENEW(16),LASTWV(16),AVROR(16)
500 DIM PROPOSAL (4,4),REPROP(4,4),BEST(4),MARK(4,4),REF(4),GAP(4,4),PR$(4)
510 DIM DISCOUNT(25,4),SALES(25),NO$(50)
```

```
520 DIM PROPO(4),REPRO(4),SCR(3),AL1(4),AL2(4),WVIEW$(4),PRDISC(4)
530 DIM GEAR(4)
600     FOR I=1 TO 50
610     READ NO$(I)
620     NEXT I
630             FOR I=1 TO FMNO
640             READ NAM$(I)
650             NEXT I
699 '
700 A$="£-Yr Option: Size= £££££: Tech= £: Cost= ££££££££: NPV= ££££££££££ ± ±"
710 LI$="              Tech     K        L        V          Max     Min"
720 LJ$="                 £  ££££.£  ££££.£  ££££.£    £££££    ££££"
730 G1$="          T           I         II        III        IV"
740 F1$="      £££        ££££       ££££       ££££       ££££"
797 '
798 ' Initialise forecasting routine:
799 '
800 P=(DEMAND(10)-DEMAND(1))/10
802     FOR J=1 TO 4
805     M(0,J)=DEMAND(1)
810             FOR I=1 TO 21
820             FORECAST(I,J)=P*I+M(0,J)
830             NEXT I
840     B(0,J)=P
850     NEXT J
860 AL1(1)=.4:AL1(2)=.4:AL1(3)=.4:AL1(4)=.2'           forecasting coeffs
870 AL2(1)=.15:AL2(2)=.15:AL2(3)=.15:AL2(4)=.08
880 OPEN "O",£1,PLANTOUT$
890 OPEN "O",£3,OUTFILE$
895 PRINT £3,DDAY,FMNO
899 '
900 T=1
910 COEF(1)=.1:COEF(2)=.15:COEF(3)=.1:COEF(4)=.05'      capital weights
999 '
1000 PRINT "Loading .... "
1010    FOR J=1 TO FMNO'        J refers to firm number
1030    INPUT £2,A
1040    FIRM(J,3)=A
1045    PLNOS(J)=A
1050    IF A=0 THEN 1300
1060            FOR I=1 TO A
1070            INPUT £2,B
1080            NOPLANTS=NOPLANTS+1
1090            OWNER(J,I)=NOPLANTS
1100            PLANT(NOPLANTS,6)=J
1110            PLANT(NOPLANTS,2)=B
1120            PLANT(NOPLANTS,1)=0
1125            IF BIGGESTP.1t.B THEN BIGGESTP=B
1130            PLANTNAME$(NOPLANTS)=NAM$(J)+"."+NO$(I)
1140            INPUT £2,PK
1150            PLANT(NOPLANTS,3)=FNPRK(PK,B)
1160            INPUT £2,PL
1170            PLANT(NOPLANTS,4)=FNPRL(PL,B)
1180            INPUT £2,PV
1190            PLANT(NOPLANTS,5)=FNPRV(PV,B)
1200                    FOR K=1 TO DDAY20
1210                    CAPACITY(K)=CAPACITY(K)+B
1220                    NEXT K
1221                    FOR L=1 TO 4
```

```
1222                    PLCOST(NOPLANTS,L)=(PLANT(NOPLANTS,3)*COEF(L))+
                        (1.1-COEF(L))*PLANT(NOPLANTS,4)
                        +(B*PLANT(NOPLANTS,5))
1223                    PLAVCOST(NOPLANTS,L)=PLCOST(NOPLANTS,L)/B
1225                    NEXT L
1228            TCOST=TCOST+PLCOST(NOPLANTS,1)
1230            NEXT I
1300    INPUT £2,IK
1310    IF A=0 THEN 1350
1320            FOR I=1 TO A
1330            IK1=IK1+PLANT(OWNER(J,I),3)
1340            NEXT I
1350    FIRM(J,1)=IK+IK1
1360    INPUT £2,ID
1370    FIRM(J,2)=ID+IK1
1380    IK1=0
1390    NEXT J
1499 '
1510 INPUT £2,PRK
1520 INPUT £2,PRL
1530 INPUT £2,PRV
1550 INPUT £2,MIN
1560 INPUT £2,MAX
1570 INPUT £2,PRICE
1580 CLOSE £2
1582    FOR I=1 TO FMNO'                  initial technologies
1584    K(I,2)=PRK
1586    L(I,2)=PRL
1588    V(I,2)=PRV
1590    MAX(I,2)=MAX
1592    MIN(I,2)=MIN
1594    NEXT I
1599 '
1600 PRDISC(1)=1.06:PRDISC(2)=1.09:PRDISC(3)=1.09:PRDISC(4)=1.06
1605            FOR J=1 TO 4
1606            DISCOUNT(1,J)=1
1607            NEXT J
1610    FOR I=2 TO 25
1615            FOR J=1 TO 4
1620            DISCOUNT(I,J)=DISCOUNT(I-1,J)/PRDISC(J)
1625            NEXT J
1630    NEXT I
1650 WVIEW$(1)="I":WVIEW$(2)="II":WVIEW$(3)="III":WVIEW$(4)="IV"
1660 GEAR(1)=.3:GEAR(2)=.5:GEAR(3)=.5:GEAR(4)=.7
1699 '
1700 PRINT £3,HEADING$
1710 PRINT £3,COMMENT$
1800    FOR I=1 TO FMNO
1810    FIRM(I,4)=GWVW
1840    NEXT I
1850 CHNG$="N"
1860 WVCH=0
1870 PRINT
1900 GOTO 2015'                           T is already = 1
2000 T=T+1
2005 IF T=DDAY THEN GOTO 12000
2015 MARK=0
```

```
2020     FOR I=1 TO 4
2025             FOR J=1 TO 4
2030             GAP(I,J)=(FORECAST(T+I+1,J)*(1.2-COEF(J)))-CAPACITY(T+I+1)
2040             IF GAP(I,J).gt.0 THEN MARK(I,J)=1:MARK=1
2045             NEXT J
2050     NEXT I
2060 '
2070     FOR J=1 TO FMNO           '              random order of firms
2072     ORDER(J)=0
2074     NEXT J
2076     FOR J=1 TO FMNO
2078     TEMP=INT(RND*FMNO)+1
2080     IF ORDER(TEMP).gt.0 THEN 2078
2082     ORDER(TEMP)=J
2084     PRINT NAM$(J);TEMP
2086     NEXT J
2088 PRINT
2100     FOR FIRMTRY=1 TO FMNO
2105     K=ORDER(FIRMTRY)
2110     PRINT NAM$(K):PRINT
2112     IF FIRM(K,1)=10 THEN GOTO 4899'       If bankrupt, ignore
2115     WVK=FIRM(K,4)' (worldview of Kth firm)
2120     FK3=FIRM(K,3)'                        Test for closures
2125     IF FK3=0 THEN 2500
2130 '
2131 '          *** Begin section B.1 ***
2132 '
2140             FOR S=1 TO FK3
2150             PKS=OWNER(K,S)
2155             IF PKS=0 THEN GOTO 2210
2160             IF PLANT(PKS,1).gt.T-10 THEN 2190
2165             IF PLANT(PKS,6).ne.K THEN 2190
2170             CHANS=RND
2180             IF CHANS.gt.0.9 THEN PRINT "Plant failure:":PRINT:KLL=PKS:
                 Z=S:GOSUB 2310
2190             NEXT S
2200     LEAST =1000
2201 '
2202 '          *** Begin section B.2 ***
2203 '
2210             FOR I=1 TO FK3
2220             IF LOSER(OWNER(K,I))=0 THEN 2290'       next I
2230             X=OWNER(K,I)
2232             IF PLANT(X,1).ge.T THEN 2290
2233             IF PLANT(X,6).ne.K THEN 2290
2234             IF PLAVCOST(X,K).gt.1.5*PRICE THEN 2240
2238             IF MARK=1 THEN 2500'    No closure if demand.gt.capacity
2240             F1=FORECAST(T+1,WVK)/CAPACITY(T+1)
2250             F2=FORECAST(T+2,WVK)/CAPACITY(T+2)
2260             LOSS =((F1/PRDISC(WVK))+(F2/(PRDISC(WVK)*PRDISC(WVK))))*
                 (PRICE-PLANT(X,5))
2263             LOSS =LOSS *PLANT(X,2)/2
2265             LOSS =LOSS -PLANT(X,4)*.5*(DISCOUNT(1,WVK)+DISCOUNT(2,WVK))
2270             LOSS =LOSS /PLANT(X,2)
2280             IF LOSS .lt.LEAST  THEN LEAST =LOSS :KLL=X:Z=I
2290             NEXT I
2300     IF LEAST .ge.0  THEN 2500
2302     GOSUB 2310
2304     GOTO 2500
```

```
2306 '
2307 '        *** Begin section B.3 ***
2308 '
2309 '   ================= Beginning of subroutine      =================
2310    FIRM(K,3)=FIRM(K,3)-1'                     Close plant no. 'KLL'
2312    PRINT £1,T
2313            FOR J=1 TO 6
2315            PRINT £1,PLANT(KLL,J)
2316            NEXT J
2318    PRINT £1,PLANTNAME$(KLL)'                  write details to disc
2320    PK2=PLANT(KLL,2)
2330    FIRM(K,1)=FIRM(K,1)-PLANT(KLL,3)
2340    PLANT(KLL,1)=-PLANT(KLL,1)
2345    IF PLANT(KLL,1)=0 THEN PLANT(KLL,1)=-.1
2348    TCOST=TCOST-PLCOST(KLL,1)
2350    NOPLANTS=NOPLANTS-1
2355    PRINT "Plant ";PLANTNAME$(KLL);"    Capacity ";PK2;"      Retired"
2360            FOR J=T TO DDAY20
2370            CAPACITY(J)=CAPACITY(J)-PK2
2380            NEXT J
2382                    FOR J=1 TO NOPLANTS+1
2383                            FOR L=1 TO FMNO
2384                            IF OWNER(L,J).gt.KLL THEN
                                OWNER(L,J)=OWNER(L,J)-1
2385                            NEXT L
2386                    NEXT J
2390                            FOR J=Z TO FK3
2400                            OWNER(K,J)=OWNER(K,J+1)
2405                            NEXT J
2410            FOR I=KLL TO NOPLANTS+1
2420            PLANTNAME$(I)=PLANTNAME$(I+1)
2425                    FOR L=1 TO 6
2430                    PLANT(I,L)=PLANT(I+1,L)
2435                    NEXT L
2437                            FOR H=1 TO 4
2438                            PLCOST(I,H)=PLCOST(I+1,H)
2440                            PLAVCOST(I,H)=PLAVCOST(I+1,H)
2442                            NEXT H
2445            NEXT I
2448                            FOR H=1 TO 4
2450                    FOR J=1 TO 4
2455                    GAP(J,H)=GAP(J,H)+PK2:IF GAP(J,H).gt.0 THEN MARK=1
2460                    NEXT J
2463                            NEXT H
2465    LEAST =0
2470    RETURN
2475 '  ================ End of subroutine     =======================
2500    PRINT:PRINT " Available technologies ":PRINT
2510    PRINT LI$:PRINT
2520            FOR L=1 TO 3
2530            PRINT USING LJ$;L;K(K,L);L(K,L);V(K,L);MAX(K,L);MIN(K,L)
2540            NEXT L
2550    PRINT
2999 '
```

```
3000 '                                          Additions; K is still firm
3001                FOR L=1 TO 4'               clear out garbage
3002                PROPO(L)=0:REPRO(L)=0:REF(L)=0
3003                     FOR J=1 TO 4
3004                     REPROP(L,J)=0:PROPOSAL(L,J)=0
3005                     NEXT J
3006                NEXT L
3007 '
3008 '       *** Begin section C.1 ***
3009 '
3010           FOR I=1 TO 4
3012      FOR TEC=1 TO 3
3014           GOSUB 5400
3015           IF K(K,TEC).le.0 THEN 3189
3016           PROPO(4)=TEC
3020           PROPO(3)=0'               Cleared from last time
3030           PROPO(1)=INT(GAP(I,WVK)/10)*10
3040           IF PROPO(1).lt.MIN THEN PROPO(1)=-10:GOTO 3189
3045           IF PROPO(1).gt.MAX THEN PROPO(1)=MAX
3050           PI1=PROPO(1)
3055           IF PI1.lt.MIN OR PI1=0 THEN 3189
3060           PROPO(2)=FNPRK(PRK,PI1)
3070           PTEMP=(PROPO(2)+FIRM(K,2))/(FIRM(K,1)+PROPO(2))
3075           IF (GEAR(WVK)*FIRM(K,1)-FIRM(K,2))/(1.05-GEAR(WVK)).le.0
               THEN PRINT "Gearing exceeded":GOTO 3189
3080           IF PTEMP.gt.GEAR(WVK) THEN PROPO(1)=
               FNINV(PRK,(GEAR(WVK)*FIRM(K,1)
               -FIRM(K,2))/(1.05-GEAR(WVK))):GOTO 3040
3090           SALES(1)=0
3100           SALES(2)=0
3110           DUM=.9*PI1:L1=FNPRL(PRL,PI1):V1=FNPRV(PRV,PI1)
3115           NPV=-PROPO(2)*(DISCOUNT(1,WVK)+DISCOUNT(2,WVK))/2
3116 '
3117 '       *** Begin section C.2. ***
3118 '
3120                FOR J=T+3 TO T+22
3130                L=J-T
3140                IF FORECAST(J,WVK).gt.DUM+CAPACITY(J) THEN
                     SALES(L)=DUM
3142                IF SALES(L)=DUM THEN 3160
3144                SALES(L)=(PI1*FORECAST(J,WVK))/(CAPACITY(J)+PI1)
3160                NPV=NPV+DISCOUNT(L,WVK)*(SALES(L)*(PRICE-V1)-L1)
3170                NEXT J
3180           PROPO(3)=NPV
3182           IF PROPO(3).le.PROPOSAL(I,3) THEN 3189
3184                     FOR J=1 TO 4
3186                     PROPOSAL(I,J)=PROPO(J)
3188                     NEXT J
3189      NEXT TEC
3190           NEXT I
3199 '
3200      TEST=1
3201 '
3202 '       *** Begin section C.3. ***
3203 '
3210           FOR J=1 TO 4                                 'find best plan
3220           IF PROPOSAL(J,3).gt.PROPOSAL(TEST,3) THEN TEST=J
3230           NEXT J
3235 '
```

```
3240            FOR J=1 TO 4
3245            IF J=TEST THEN X$="*" ELSE X$=" "
3250            PRINT USING A$;J+1;PROPOSAL(J,1);PROPOSAL(J,4);
                PROPOSAL(J,2);PROPOSAL(J,3);X$
3260            NEXT J
3270      PRINT
3280      PRINT "Option ";TEST+1;" selected provisionally":PRINT
3999 '
4000      MARK2=0'                      replacement of existing plant
4002      N=FIRM(K,3)
4004      C1=0
4010                          FOR M=1 TO N
4015                          TMPAVCOST(M)=PLAVCOST(OWNER(K,M),WVK)
4020                          MRK(M)=M
4025                          NEXT M
4026 '
4027 '          *** Begin section C.4 ***
4028 '
4030            FOR TRIAL1=1 TO N'                order plants by costs
4035                  FOR TRIAL2=1 TO N-1
4040                  IF TMPAVCOST(TRIAL2).1t.TMPAVCOST(TRIAL2+1) THEN
                      SWAP TMPAVCOST(TRIAL2),TMPAVCOST(TRIAL2+1):
                      SWAP MRK(TRIAL2),MRK(TRIAL2+1)
4045                  NEXT TRIAL2
4050            NEXT TRIAL1
4055                  FOR TRIAL=1 TO N
4060                  PRINT PLANTNAME$(OWNER(K,MRK(TRIAL)));TMPAVCOST(TRIAL)
4065                  NEXT TRIAL
4070            PRINT
4075 '
4076 '          *** Begin section D.1 ***
4077 '
4080            FOR TRIAL=1 TO N'                 find value of present plant
4085            I=MRK(TRIAL)
4090            NPV=0
4095            Q=OWNER(K,I)
4100            IF PLANT(Q,1).gt.T THEN NPV=-PLANT(Q,3)*DISCOUNT(1,WVK)/2
4105            L=PLANT(Q,4)
4110            V=PLANT(Q,5)
4115            CAP=PLANT(Q,2)*.9
4120                  FOR J=T+1 TO T+22
4125                  H=J-T
4130                  IF FORECAST(J,WVK).gt.CAPACITY(J)-C1 THEN
                       SALES(H)=CAP:GOTO 4140
4135                  SALES(H)=(CAP*FORECAST(J,WVK))/(CAPACITY(J)-C1)
4140                  NPV=NPV+(SALES(H)*(PRICE-V)-L)*DISCOUNT(H,WVK)
4145                  NEXT J
4150            VALUE(I)=NPV
4155            PRINT PLANTNAME$(Q);" has marginal present value ";NPV
4160            C1=C1+CAP
4165            NEXT TRIAL
4170                  FOR L=1 TO 3
4175                  BEST(L)=0
4180                  NEXT L
4199 '
```

```
4200            FOR I=1 TO 4'                     2,3,4,5-year plans
4201 '
4202 '         *** Begin section D.2 ***
4203 '
4212    FOR TEC=1 TO 3
4214            GOSUB 5400
4216            IF K(K,TEC).le.0 THEN 4448
4218            REPRO(4)=TEC
4220            G=GAP(I,WVK)
4225            G1=0
4227            VL=0
4228            LIMIT=0
4230                    FOR TRIAL=1 TO N
4231                    IF LIMIT=1 THEN 4425
4232                    J=MRK(TRIAL)
4235                    VL=VL+VALUE(J)
4240                    G1=G1+PLANT(OWNER(K,J),2)
4245                    IF G+G1.lt.MIN THEN 4420
4250                    REPRO(1)=INT((G1+G)/10)*10
4260                    IF G+G1.gt.MAX THEN REPRO(1)=MAX:LIMIT=1
4270                    RI1=REPRO(1)
4275                    IF RI1.lt.MIN OR RI1=0 THEN 4420
4280                    REPRO(2)=FNPRK(PRK,RI1)
4283                    IF (GEAR(WVK)*FIRM(K,1)-FIRM(K,2))/.7.le.0 THEN
                        PRINT "Gearing exceeded":REPRO(3)=-1:GOTO 4448
4285                    IF (REPRO(2)+FIRM(K,1))*GEAR(WVK).lt.FIRM(K,2)+
                         REPRO(2) THEN REPRO(1)=FNINV(PRK,(GEAR(WVK)*FIRM(K,1)
                         -FIRM(K,2))/(1.05-GEAR(WVK))):GOTO 4270
4290                    SALES(1)=0:SALES(2)=0
4300                    DUM=.9*RI1:L1=FNPRL(PRL,RI1)
4310                    NPV=-REPRO(2):V=FNPRV(PRV,RI1)
4311 '
4312 '         *** Begin section D.3.
4313 '
4320                            FOR L=T+3 TO T+22
4325                            H=L-T
4330                            IF FORECAST(L,WVK).gt.DUM+CAPACITY(L)-G1 THEN
                                SALES(H)=DUM:GOTO 4340
4338                            SALES(H)=(RI1*FORECAST(L,WVK))
                                /(RI1+CAPACITY(L)-G1)
4340                            NPV=NPV+DISCOUNT(H,WVK)*
                                (SALES(H)*(PRICE-V)-L1)
4350                            NEXT L
4360                    REPRO(3)=NPV
4365                    IF NPV.lt.VL THEN REPRO(1)=-2:GOTO 4420
4370                    IF NPV.le.BEST(3) THEN 4420
4380                            FOR L=1 TO 3
4390                            BEST(L)=REPRO(L)
4400                            NEXT L
4410                    REF(I)=TRIAL
4415                    IF LIMIT=1 THEN 4425
4420                    NEXT TRIAL
```

```
4421 '
4422 '          *** Begin section D.4 ***
4423 '
4425            VL=0
4430                            FOR L=1 TO 3
4432                            REPRO(L)=BEST(L)
4433                            BEST(L)=0
4434                            NEXT L
4435            IF REF(I)=0 THEN 4448
4436                    FOR TRIAL=1 TO REF(I)
4437                    J=MRK(TRIAL):VL=VL+VALUE(J)
4438                    NEXT TRIAL
4439            IF VL.gt.REPRO(3) THEN REPRO(1)=-1:REPRO(3)=-REPRO(3)
4440            IF REPRO(3).le.REPROP(I,3) THEN 4448
4442                    FOR J=1 TO 4
4444                    REPROP(I,J)=REPRO(J)
4446                    NEXT J
4448    NEXT TEC
4449            NEXT I'                    now choose best plan and execute
4449 '
4449 '          *** Begin section E.1 ***
4449 '
4450                    FOR L=1 TO 4
4460                    PRINT"Option ";L+1;"retires";REF(L);" NPV=";
                        REPROP(L,3);"   Size ";REPROP(L,1);" Tech=";
                        REPROP(L,4)
4480                    NEXT L
4490 '
4500            FOR I=1 TO 4
4505            REF(I)=0
4510            IF REPROP(I,3).le.PROPOSAL(TEST,3) THEN 4550
4520                    FOR L=1 TO 4
4530                    PROPOSAL(TEST,L)=REPROP(I,L)
4540                    NEXT L
4550            NEXT I
4560 '                                            execution follows....
4561 '
4562 '          *** Begin section E.2 ***
4563 '
4600    PRINT:PT1=PROPOSAL(TEST,1)
4602    IF PROPOSAL(TEST,3).le.0 THEN PRINT "No builds":GOTO 4840
4605    IF PT1.lt.MIN(K,PROPOSAL(TEST,4)) THEN PRINT "No builds":GOTO 4840
4610    PRINT "Opt to build plant size ";PT1;"         NPV = ";
        PROPOSAL(TEST,3)
4612    IF PROPOSAL(TEST,4).ne.1 THEN 4620 ELSE TOGGLE=1
4613    K(K,1)=RK(K):L(K,1)=RL(K):V(K,1)=RV(K)' insert real technology
4614    MAX(K,1)=RMAX(K):MIN(K,1)=RMIN(K)
4615    RK(K)=0:RL(K)=0:RV(K)=0
4616    RMAX(K)=0:RMIN(K)=0
4617    IF PT1.gt.MAX(K,1) THEN PT1=MAX(K,1):PRINT "Size reduced to ";PT1
4618    IF PT1.lt.MIN(K,1) THEN PT1=MIN(K,1):PRINT "Size increased to ";PT1
4619    IF PT1.le.0 THEN PRINT "Build aborted; .le.0":GOTO 4840
4620    FIRM(K,3)=FIRM(K,3)+1
4625    PLNOS(K)=PLNOS(K)+1
4630    NOPLANTS=NOPLANTS+1
4633    TEC=PROPOSAL(TEST,4)
4636    GOSUB 5400
4640    OWNER(K,FIRM(K,3))=NOPLANTS
4650    PLANT(NOPLANTS,1)=T+2
```

```
4660    PLANT(NOPLANTS,2)=PT1
4670    PLANT(NOPLANTS,3)=FNPRK(PRK,PT1)
4680    PLANT(NOPLANTS,4)=FNPRL(PRL,PT1)
4690    PLANT(NOPLANTS,5)=FNPRV(PRV,PT1)
4700    PLANT(NOPLANTS,6)=K
4705    IF BIGGESTP.lt.PT1 THEN BIGGESTP=PT1
4710            FOR I=T+2 TO DDAY20
4720            CAPACITY(I)=CAPACITY(I)+PT1
4730            NEXT I
4740    PLANTNAME$(NOPLANTS)=NAM$(K)+"."+NO$(PLNOS(K))
4760            FOR I=1 TO 4
4765            PROPO(I)=0:REPRO(I)=0
4767                    FOR J=1 TO 4
4770                    MARK(I,J)=0
4775                    GAP(I,J)=GAP(I,J)-PT1
4777                    IF GAP(I,J).gt.0 THEN MARK=1
4779                    NEXT J
4780            FOR L=1 TO 4
4790            REPROP(I,L)=0
4800            PROPOSAL(I,L)=0
4810            NEXT L
4820            NEXT I
4822                    FOR J=1 TO 4
4825                    PLCOST(NOPLANTS,J)=(PLANT(NOPLANTS,3)*COEF(J))+
                        (1.1-COEF(J))*PLANT(NOPLANTS,4)
                        +(PLANT(NOPLANTS,5)*PT1)
4827                    PLAVCOST(NOPLANTS,J)=PLCOST(NOPLANTS,J)/PT1
4829                    NEXT J
4830 '
4831 '          *** Begin section F.1 ***
4832 '
4840 '                                          discard poor technology
4842    IF TOGGLE=1 THEN TOGGLE=0 ELSE 4860
4843    Q=K
4844    GOSUB 10070
4846    WS=WSTECNO
4848    K(K,WS)=K(K,1):K(K,1)=0
4850    L(K,WS)=L(K,1):L(K,1)=0
4852    V(K,WS)=V(K,1):V(K,1)=0
4854    MAX(K,WS)=MAX(K,1):MAX(K,1)=0
4856    MIN(K,WS)=MIN(K,1):MIN(K,1)=0
4860    IF WVK.ne.3 THEN 4899
4865    IF K(K,1).le.0 OR PLANT(OWNER(K,FIRM(K,3)),1)=T+2 THEN 4899
4870    IF FIRM(K,1)*.4.lt.FIRM(K,2) THEN 4899
4875    IF MIN(K,1)=0 THEN PT1=10 ELSE PT1=MIN(K,1)
4877    IF PT1.gt.BIGGESTP*.5 THEN 4899
4880    PROPOSAL(TEST,4)=1
4885    PRINT:PRINT "Experimental build, size ";PT1:PRINT
4890    GOTO 4612
4899    PRINT "            ------------------------":PRINT
4900    NEXT FIRMTRY
```

```
5000 '                                       cashflows
5001 '
5002 '          *** Begin section G.1 ***
5003 '
5010    FOR I=1 TO NOPLANTS'                 building first
5020    PLINCOME(I)=0
5030    LOSER(I)=0
5035    IF PLANT(I,1)=T THEN TCOST=TCOST+PLCOST(I,1)
5040    IF PLANT(I,1).le.T THEN 5090
5050    PI6=PLANT(I,6)
5060    COST=PLANT(I,3)/2
5070    FIRM(PI6,1)=FIRM(PI6,1)+COST
5080    FIRM(PI6,2)=FIRM(PI6,2)+COST
5090    NEXT I
5100 PR=DEMAND(T)/CAPACITY(T)
5110 IF PR.gt.1  THEN PR=1
5120            FOR J=1 TO FMNO
5130            FINCOME(J)=0
5140            NEXT J
5142 P=DEMAND(T)/CAPACITY(T)
5144 AVCOST=TCOST/CAPACITY(T)
5146 PRICE=AVCOST*(.25+P)
5148 IF CAPACITY(T)=0 THEN PRICE=35
5150 '                                       revenues
5160    FOR I=1 TO NOPLANTS
5170    IF PLANT(I,1).gt.T THEN 5220
5180    INCOME=PR*PLANT(I,2)*(PRICE-PLANT(I,5))-PLANT(I,4)
5190    IF INCOME.lt.0 THEN LOSER(I)=1
5200    FINCOME(PLANT(I,6))=FINCOME(PLANT(I,6))+INCOME
5210    PLINCOME(I)=INCOME
5220    NEXT I
5221 '
5222 '          *** Begin section G.2 ***
5223 '
5230 '                                       sum revenues, add interest charge
5235 AVROR=0
5240            FOR J=1 TO FMNO
5250            FIRM(J,2)=FIRM(J,2)-FINCOME(J)
5260            INTEREST(J)=FIRM(J,2)*.05
5265            IF FIRM(J,2).lt.0 THEN INTEREST(J)=FIRM(J,2)*.03
5270            FIRM(J,2)=FIRM(J,2)+INTEREST(J)
5275            FMROR(J)=100*(FINCOME(J)-INTEREST(J))/(FIRM(J,1)-FIRM(J,2))
5276            IF FINCOME(J)-INTEREST(J).lt.0 AND FMROR(J).gt.0 THEN
                FMROR(J)=-FMROR(J)
5277            IF FIRM(J,2).lt.0 THEN FIRM(J,2)=FIRM(J,2)
                +(FINCOME(J)-INTEREST(J))*.4              'dividends
5278            AVROR(J)=.5*(AVROR(J)+FMROR(J))
5279            AVROR=AVROR+AVROR(J)
5280            NEXT J
5285 AVROR=AVROR/FMNO
5290 '
5300 PRINT £3,T'                             report to disc file
5310 PRINT £3,CAPACITY(T),DEMAND(T),PRICE
5320    FOR I=1 TO FMNO
5330            FOR J=1 TO 4
5340            PRINT £3, FIRM(I,J)
5350            NEXT J
5360    NEXT I
5370 PRINT £3,-999
```

```
5380     FOR K=1 TO FMNO
5381             FOR I=1 TO FIRM(K,3)
5382             Y=OWNER(K,I)
5383             IF PLANT(Y,6).ne.K THEN PRINT "Scream     ";CHR$(7);
                 "firm";K;"plant";I;"   Y";Y:STP$="S"
5384             NEXT I
5385     NEXT K
5390 GOTO 5800
5399 '   ================= Beginning of subroutine       =================
5400 '                          subroutine for considering technologies
5410                                    PRK=K(K,TEC)
5420                                    PRL=L(K,TEC)
5430                                    PRV=V(K,TEC)
5440                                    MAX=MAX(K,TEC)
5450                                    MIN=MIN(K,TEC)
5460                                    RETURN
5499 '   ================= End of subroutine       ========================
5800 '                                  general report
5810 PRINT
5820 PRINT "Time period ";T
5830 PRINT "Demand = ";DEMAND(T);"    Capacity = ";CAPACITY(T)
5850 PRINT "Capacity utilisation factor = ";P
5860 PRINT "Price = ";PRICE;"     Average ROR = ";AVROR
5870 PRINT
5880 STP$=INKEY$
5890 '                                  recycles bankrupt firms
5895     FOR I=1 TO FMNO
5900     IF FIRM(I,2).le.0.8*FIRM(I,1) OR FIRM(I,3).gt.0 THEN 5970
5905     RENEW(I)=1
5915     LASTINNOV(I)=0
5917     FMROR(I)=0:AVROR(I)=0
5920             FOR J=1 TO 3
5925             K(I,J)=0:L(I,J)=0:V(I,J)=0
5930             MAX(I,J)=0:MIN(I,J)=0
5935             NEXT J
5940     RK(I)=0:RL(I)=0:RV(I)=0
5945     RMAX(I)=0:RMIN(I)=0
5950     FIRM(I,1)=10
5955     FIRM(I,2)=0
5960     FIRM(I,3)=0
5965     FIRM(I,4)=1
5970     NEXT I
5990 GOTO 6006
5999 '
6000 PRINT: PRINT "Press any key to continue"
6002 Z$=INKEY$
6004 IF Z$="" THEN 6002
6006 PRINT "Report options"
6010 PRINT "1. Firm status and cashflows":PRINT
6020 PRINT "2. Plant listings":PRINT
6030 PRINT "3. Available technologies":PRINT
6040 PRINT "4. Forecasts":PRINT
6050 PRINT "5. Quit- next time period":PRINT
6055 IF STP$="S" OR STP$="s" THEN 6060 ELSE 7000
6060 INPUT "Type choice 1/2/3/4/5 ";A
6070 IF A.lt.1 OR A.gt.5 THEN 6060
6080 ON A GOTO 6100,6200,6300,6400,7000
6099 '
6100 PRINT
```

```
6110 D$="  Name        Capital     Debt       Income   Interest AvROR Plants  VoW"
6112 E$="±           ±££££££££  ££££££££   £££££££     ££££££ £££.£     ££  ±  ±"
6114 PRINT D$:PRINT
6120    FOR I=1 TO FMNO
6130    PRINT USING E$;NAM$(I);FIRM(I,1);FIRM(I,2);FINCOME(I);INTEREST(I);
        AVROR(I);FIRM(I,3);WVIEW$(FIRM(I,4))
6140    NEXT I
6150 GOTO 6000
6199 '
6200 PRINT "There are ";NOPLANTS;" plants at T = ";T
6210 PRINT
6212 F$="   Name             Capacity  Built    Cost       L      V    Avc/I  Avc/R"
6214 G$="±                 ±££££££££  ££££   ££££££££  £££££££ ££££.£ ££.££  ££.££"
6220 PRINT F$:PRINT
6230    FOR I=0 TO NOPLANTS+1
6240    PRINT USING G$;PLANTNAME$(I);PLANT(I,2);PLANT(I,1);PLANT(I,3);
        PLANT(I,4);PLANT(I,5);PLAVCOST(I,1);PLAVCOST(I,FIRM(PLANT(I,6),4))
6250    NEXT I
6260 GOTO 6000
6299 '
6300 PRINT
6310 PRINT "Available technologies:"
6320 PRINT:PRINT LI$:PRINT
6330    FOR I=1 TO FMNO
6340    PRINT NAM$(I)
6350            FOR J=1 TO 3
6360            IF K(I,J).le.0 THEN 6380
6370            PRINT USING LJ$;J;K(I,J);L(I,J);V(I,J);MAX(I,J);MIN(I,J)
6380            NEXT J
6390    PRINT
6394    NEXT I
6396 GOTO 6000
6399 '
6400 PRINT
6410 INPUT "Forecasts up to T = ";TT
6415 PRINT:PRINT G1$:PRINT
6420    FOR I=T TO TT
6430    PRINT USING F1$;I;FORECAST(I,1);FORECAST(I,2);FORECAST(I,3);
        FORECAST(I,4)
6440    NEXT I
6450 GOTO 6000
6998 '
6999 '          *** Begin section H.1 ***
7000 '                                  Forecasting module
7005    FOR I=1 TO 4
7010    E(T,I)=DEMAND(T)-FORECAST(T,I)
7020    M(T,I)=M(T-1,I)+B(T-1,I)+AL1(I)*E(T,I)
7030    B(T,I)=B(T-1,I)+AL2(I)*E(T,I)
7040            FOR J=1 TO 22
7050            FORECAST(J+T,I)=M(T,I)+J*B(T,I)
7060            IF J+T.gt.DDAY THEN FORECAST(J+T,I)=FORECAST(DDAY,I)
7070            NEXT J
7080    NEXT I
7999 '
8000 '                                  Change world views (not used)
8005 IF WVCH.ne.1 THEN 9000
8999 '
```

```
9000 '                                      Technical improvements
9010 PRINT:PRINT "Technical changes":PRINT:PRINT LI$
9020    FOR I=1 TO FMNO
9034    IF K(I,1).le.0 THEN CHECK=1 ELSE CHECK=0
9036    IF CHECK=0 AND LASTINNOV(I)+10.gt.T THEN 9120 ELSE GOSUB 10000
9038    IF K(I,1).gt.0 AND FMROR(I).gt.0 THEN 9120'     only innovate once
9040    PRINT:PRINT NAM$(I):PRINT
9050    CHANS=RND
9052    WVI=FIRM(I,4)
9054    IF RENEW(I)=1 THEN RENEW(I)=0:GOSUB 9160 ELSE 9058
9056    GOTO 9110
9058    CHANS=RND'                                         radicals
9060    IF CHANS.le.0.05 AND WVI=1 THEN GOSUB 9480 ELSE 9064
9062    GOTO 9110
9064    IF CHANS.le.0.02 AND WVI=2 THEN GOSUB 9480 ELSE 9068
9066    GOTO 9110
9068    IF CHANS.le.0.1 AND WVI=3 THEN GOSUB 9480 ELSE 9072
9070    GOTO 9110
9072    IF CHANS.le.0.05 AND WVI=4 THEN GOSUB 9480 ELSE 9076
9074    GOTO 9110
9076    CHANS=RND'                                         imitations
9078    IF FMROR(I).le.0 THEN ROR=1 ELSE ROR=0
9080    IF CHANS.le.0.3 AND WVI=1 THEN GOSUB 9150 ELSE 9084
9082    GOTO 9110
9084    IF CHANS.le.0.3+.2*ROR AND WVI=2 THEN GOSUB 9150 ELSE 9088
9086    GOTO 9110
9088    IF CHANS.lt.0.2+.1*ROR AND WVI=3 THEN GOSUB 9150 ELSE 9092
9090    GOTO 9110
9092    IF CHANS.lt.0.1+.2*ROR AND WVI=4 THEN GOSUB 9150 ELSE GOSUB 9630
9110    PRINT USING LJ$;1;K(I,1);L(I,1);V(I,1);MAX(I,1);MIN(I,1)
9115    IF K(I,1).gt.0 THEN LASTINNOV(I)=T
9120    NEXT I
9130    GOTO 2000
9140 '
9150 '  ================ Beginning of subroutine      ================
9160 SX=I:MAXROR=-1000'                          imitation
9170 Q=I
9180 GOSUB 10070
9190 WS=WSTECNO
9200 IF WS=1 THEN 9260
9210 SWAP K(I,1),K(I,WS)
9220 SWAP L(I,1),L(I,WS)
9230 SWAP V(I,1),V(I,WS)
9240 SWAP MAX(I,1),MAX(I,WS)
9250 SWAP MIN(I,1),MIN(I,WS)
9260 GOSUB 10000
9270    FOR J=1 TO FMNO
9280    IF FMROR(J).gt.MAXROR THEN SX=J:MAXROR=FMROR(J)
9290    NEXT J
9300 Q=SX
9310 IF Q=I THEN 9450
9320 GOSUB 10070
9330 BT=BSTECNO
9340 IF BT=1 AND WSTECNO=2 THEN BT=3'            can't imitate experiments
9350 IF BT=1 AND WSTECNO=3 THEN BT=2
9360 RK(I)=K(Q,BT):K(I,1)=RK(I)*(.9+(.2*RND))
9370 RL(I)=L(Q,BT):L(I,1)=RL(I)*(.9+(.2*RND))
9380 RV(I)=V(Q,BT):V(I,1)=RV(I)*(.975+(.05*RND))
9390 RMAX(I)=MAX(Q,BT):MAX(I,1)=INT((RMAX(I)*(.9+(.2*RND)))/10)*10
```

```
9400 RMIN(I)=MIN(Q,BT):MIN(I,1)=INT((RMIN(I)*(.9+(.2*RND)))/10)*10
9410 Q=I
9420 GOSUB 10070
9430 IF BSTECNO=1 THEN 9450
9440 GOSUB 10000
9450 RETURN
9460 '  ================= End of subroutine      ========================
9470 '  ================= Beginning of subroutine        =================
9480 '                           major/radical innovation (not used)
9481 GOTO 9620
9600 '  ================= End of subroutine      ========================
9610 '  ================= Beginning of subroutine        =================
9620 '                                                incremental innovation
9630 CHANS=RND
9632 Q=I:GOSUB 10070
9634 BT=BSTECNO
9635 IF BIGGESTP.gt.0.2*DEMAND(T) THEN 9646
9636 IF FIRM(I,3).gt.4 THEN FM=FIRM(I,3)-4 ELSE FM=0
9638 IF WVI=1 AND CHANS.lt.0.2+FM THEN 9830
9640 IF WVI=2 AND CHANS.lt.0.1+FM THEN 9830
9642 IF WVI=3 AND CHANS.lt.0.2+FM THEN 9830
9644 IF WVI=4 AND CHANS.lt.0.4+FM THEN 9830
9646 IF WVI=1 OR WVI=3 THEN 9652
9648 IF WVI=2 THEN 9658
9650 IF WVI=4 THEN 9664
9652 IF CHANS.lt.0.8 THEN INK=.2:INL=.2:GOTO 9690
9654 IF CHANS.lt.0.9 THEN INK=.05:INL=.25:GOTO 9690
9656 INK=.25:INL=.05:GOTO 9690
9658 IF CHANS.lt.0.4 THEN INK=.2:INL=.2:GOTO 9690
9660 IF CHANS.lt.0.5 THEN INK=.05:INL=.25:GOTO 9690
9662 INK=.25:INL=.05:GOTO 9690
9664 IF CHANS.lt.0.6 THEN INK=.2:INL=.2:GOTO 9690
9666 INK=.05:INL=.25
9690 RV(I)=V(I,BT)*(.975+(.05*RND))
9700 V(I,1)=RV(I)*(.975+(.05*RND))
9710 RK(I)=K(I,BT)*((1-INK)+(2*INK*RND))
9720 K(I,1)=RK(I)*(.9+(.2*RND))
9730 RL(I)=L(I,BT)*((1-INL)+(2*INL*RND))
9740 L(I,1)=RL(I)*(.9+(.2*RND))
9750 RMAX(I)=INT((MAX(I,BT)*(.9+(.2*RND)))/10)*10
9760 MAX(I,1)=INT((RMAX(I)*(.9+(.2*RND)))/10)*10
9770 RMIN(I)=10+INT((MIN(I,BT)*(.9+(.2*RND)))/10)*10
9780 MIN(I,1)=INT((RMIN(I)*(.9+(.2*RND)))/10)*10
9790 Q=I
9800 GOSUB 10070
9810 IF BSTECNO=1 THEN 9970 ELSE GOSUB 10000
9820 GOTO 9970
9830 RV(I)=V(I,BT)*(.975+(.05*RND))'              scaleup
9840 V(I,1)=RV(I)*(.975+(.05*RND))
9850 RK(I)=K(I,BT)*(.95+(.1*RND))
9860 K(I,1)=RK(I)*(.95+(.1*RND))
9870 RL(I)=L(I,BT)*(.95+(.1*RND))
9880 L(I,1)=RL(I)*(.95+(.1*RND))
9890 RMAX(I)=INT((MAX(I,BT)*(.5+2*RND))/10)*10
9900 MAX(I,1)=INT((RMAX(I)*(.9+(.2*RND)))/10)*10
9910 RMIN(I)=10+INT((MIN(I,BT)*(.5+(4.5*RND)))/10)*10
9920 MIN(I,1)=INT((RMIN(I)*(.9+(.2*RND)))/10)*10
9930 IF MIN(I,1).ge.MAX(I,1) THEN GOSUB 10000
9940 Q=I
```

```
9950 GOSUB 10070
9960 IF BSTECNO.ne.1 THEN GOSUB 10000
9970 RETURN
9980 '  ================= End of subroutine      ========================
9990 '  ================= Beginning of subroutine      =================
10000 K(I,1)=0:RK(I)=0'                          kills duds
10010 L(I,1)=0:RL(I)=0
10020 V(I,1)=0:RV(I)=0
10030 MIN(I,1)=0:RMIN(I)=0
10040 MAX(I,1)=0:RMAX(I)=0
10050 RETURN
10060 ' ================= End of subroutine      ========================
10070 ' ================= Beginning of subroutine      =================
10080 '                                    find the best technology
10090 SCR(1)=0:SCR(2)=0:SCR(3)=0
10100   FOR M=1 TO 3
10110   PRINT USING LJ$;M;K(Q,M);L(Q,M);V(Q,M);MAX(Q,M);MIN(Q,M)
10120   IF M=1 THEN Y=1:Z=2
10130   IF M=2 THEN Y=1:Z=3
10140   IF M=3 THEN Y=2:Z=3
10150   IF K(Q,Y).le.0 AND K(Q,Z).gt.0 THEN SCR(Z)=SCR(Z)+5:GOTO 10560
10160   IF K(Q,Z).le.0 AND K(Q,Y).gt.0 THEN SCR(Y)=SCR(Y)+5:GOTO 10560
10170 '
10180   IF MIN(Q,Y).lt.MIN(Q,Z) THEN SCR(Y)=SCR(Y)+1:MINU=MIN(Q,Z)
10190   IF MIN(Q,Z).lt.MIN(Q,Y) THEN SCR(Z)=SCR(Z)+1:MINU=MIN(Q,Y)
10200   IF MAX(Q,Y).gt.MAX(Q,Z) THEN SCR(Y)=SCR(Y)+1:MAXU=MAX(Q,Z)
10210   IF MAX(Q,Z).gt.MAX(Q,Y) THEN SCR(Z)=SCR(Z)+1:MAXU=MAX(Q,Y)
10220   MIQY=MIN(Q,Y):MIQZ=MIN(Q,Z):ZZZ=MIQY-MIQZ
10230   IF ZZZ=0 THEN 10240 ELSE 10300'avoids compiler error
10240   MINU=MIN(Q,Y):IF MINU=0 THEN 10300
10250   A=FNTCOMP(MINU,K(Q,Y),L(Q,Y),V(Q,Y),FIRM(Q,4))
10260   B=FNTCOMP(MINU,K(Q,Z),L(Q,Z),V(Q,Z),FIRM(Q,4))
10270   IF A.lt.B THEN SCR(Y)=SCR(Y)+1
10280   IF B.lt.A THEN SCR(Z)=SCR(Z)+1
10290   IF A=B THEN SCR(Y)=SCR(Y)+.5:SCR(Z)=SCR(Z)+.5
10300   MAQY=MAX(Q,Y):MAQZ=MAX(Q,Z):ZZZ=MAQY-MAQZ
10310   IF ZZZ=0 THEN 10320 ELSE 10380
10320   MAXU=MAX(Q,Y):IF MAXU=0 THEN 10560
10330   A=FNTCOMP(MAXU,K(Q,Y),L(Q,Y),V(Q,Y),FIRM(Q,4))
10340   B=FNTCOMP(MAXU,K(Q,Z),L(Q,Z),V(Q,Z),FIRM(Q,4))
10350   IF A.lt.B THEN SCR(Y)=SCR(Y)+1
10360   IF B.lt.A THEN SCR(Z)=SCR(Z)+1
10370   IF A=B THEN SCR(Y)=SCR(Y)+.5:SCR(Z)=SCR(Z)+.5
10380   IF MINU=0 THEN 10440
10390   A=FNTCOMP(MINU,K(Q,Y),L(Q,Y),V(Q,Y),FIRM(Q,4))
10400   B=FNTCOMP(MINU,K(Q,Z),L(Q,Z),V(Q,Z),FIRM(Q,4))
10410   IF A.lt.B THEN SCR(Y)=SCR(Y)+1
10420   IF B.lt.A THEN SCR(Z)=SCR(Z)+1
10430   IF A=B THEN SCR(Y)=SCR(Y)+.5:SCR(Z)=SCR(Z)+.5
10440   IF MAXU=0 THEN 10560
10450   A=FNTCOMP(MAXU,K(Q,Y),L(Q,Y),V(Q,Y),FIRM(Q,4))
10460   B=FNTCOMP(MAXU,K(Q,Z),L(Q,Z),V(Q,Z),FIRM(Q,4))
10470   IF A.lt.B THEN SCR(Y)=SCR(Y)+1
10480   IF B.lt.A THEN SCR(Z)=SCR(Z)+1
10490   IF A=B THEN SCR(Y)=SCR(Y)+.5:SCR(Z)=SCR(Z)+.5
10500   MIDU=(MAXU+MINU)/2
10510   A=FNTCOMP(MIDU,K(Q,Y),L(Q,Y),V(Q,Y),FIRM(Q,4))
10520   B=FNTCOMP(MIDU,K(Q,Z),L(Q,Z),V(Q,Z),FIRM(Q,4))
10530   IF A.lt.B THEN SCR(Y)=SCR(Y)+1
```

```
10540   IF B.1t.A THEN SCR(Z)=SCR(Z)+1
10550   IF A=B THEN SCR(Y)=SCR(Y)+.5:SCR(Z)=SCR(Z)+.5
10560   NEXT M
10570 BSTECNO=1:WSTECNO=3
10580 IF SCR(2).ge.SCR(1) AND SCR(2).ge.SCR(3) THEN BSTECNO=2
10590 IF SCR(3).ge.SCR(1) AND SCR(3).ge.SCR(2) THEN BSTECNO=3
10600 IF SCR(1).1e.SCR(2) AND SCR(1).1e.SCR(3) THEN WSTECNO=1
10610 IF SCR(2).1e.SCR(1) AND SCR(2).1e.SCR(3) THEN WSTECNO=2
10620 PRINT SCR(1);SCR(2);SCR(3):PRINT "best=";BSTECNO;"    worst=";WSTECNO
10630 RETURN
10640 ' ================= End of subroutine    =========================
11000 DATA "1","2","3","4","5","6","7","8","9","10","11","12","13","14","15"
11010 DATA "16","17","18","19","20","21","22","23","24","25","26","27","28"
11020 DATA "29","30","31","32","33","34","35","36","37","38","39","40"
11030 DATA "41","42","43","44","45","46","47","48","49","50"
11040 DATA "ONE","TWO","THREE","FOUR","FIVE","SIX","SEVEN","EIGHT","NINE"
11050 DATA "TEN","ELEVEN","TWELVE","THIRTEEN","FOURTEEN","FIFTEEN","SIXTEEN"
11060 DATA "SEVENTEEN","EIGHTEEN","NINETEEN","TWENTY","TWENTYONE","TWENTYTWO"
11070 DATA "TWENTYFOUR","TWENTYFIVE","TWENTYSIX","TWENTYSEVEN","TWENTYEIGHT"
11080 DATA "TWENTYNINE","THIRTY"
12000   FOR I=1 TO NOPLANTS'            plant data records
12010   PRINT £1,T+1
12020           FOR J=1 TO 6
12030           PRINT £1,PLANT(I,J)
12040           NEXT J
12050   PRINT £1,PLANTNAME$(I)
12060   NEXT I
12070 END
```

Appendix 8B: Arrays used in EMIR version 3.2

Related to time series:

DEMAND(t)	Industry demand at period t
CAPACITY(t)	Industry capacity (or forecast capacity) at time t
FORECAST(t,wv)	Forecast for time t held by firms with worldviews wv
M(t,wv)	(Forecasting para-
E(t,wv)	(meters for time t,
B(t,wv)	(worldview wv
DISCOUNT(20,wv)	Discount factors for next 20 periods for worldview wv

Related to Firms:

FIRM(i,4)	Firm i's Capital (1), Debt (2), number of plants in operation (3) and worldview (4)
NAM$(i)	Name of firm i
INTEREST(i)	This period interest charge for firm i
FINCOME(i)	Income this period for firm i
PLNOS(i)	Number of plants operated by firm i
FMROR(i)	Rate of return for firm i this period
AVROR(i)	(Exponentially-weighted moving average) rate of return for firm i
ORDER(i)	(Random) order in which firm i takes its capacity decisions for this period
LASTINNOV(i)	Time period at which firm i last found technological innovation
K(i,j)	(jth technology Capital coefficient for firm i
L(i,j)	(" " Labour " " " i
V(i,j)	(" " Variable " " " i
MAX(i,j)	(" " Maximum plant scale " " i
MIN(i,j)	(" " Minimum " " " " i
OWNER(i,j)	Reference number (i.e. index of array PLANT below) of jth firm owned by firm i
RENEW(i)	1 if firm i has been bankrupted, 0 else

Related to Plants:

PLANT(i,6)	Plant i's date of first becoming operational (1), production capacity (2), Capital construction cost (3), Labour cost per period (4), Variable cost per unit of output (5), and reference number (i.e. index of array FIRM above) of owner (6)
PLANTNAME$(i)	Name of plant i
LOSER(i)	1 if plant lost money last period, 0 else
VALUE(i)	Last calculated NPV of ith plant
PLINCOME(i)	Income this period of plant i
PLCOST(i,wv)	Production cost of ith plant as judged by firm with worldview wv
PLAVCOST(i)	Actual production cost per unit of output of plant i
TMPAVCOST(i)	Intermediate calculating variable for ith plant

Related to plant construction decisions:

(Used for different purposes in different places, and results not stored - listed for completeness)

PROPOSAL(i,j)
REPROP(i,j)
BEST(i)
MARK(i,j)
MRK(i)
REF(i)
GAP(i,j)
PR$(i)
PROPO(i)
REPRO(i)
SCR(i)
GEAR(i)
MRK(i)

Appendix 8C: EMIR Program Logical Structure

Labels in the left-hand column are reproduced as comment lines in the program listing (Appendix 8A).

```
LABEL    FUNCTION

A        Declare array variables
         Initialise
         Read data files

         FOR t = 1 to "enddate"

            FOR firm = 1 to "no of firms"

B.1            Test plants owned by firm for random failure
B.2            Test plants owned by firm for retirement because loss-making

B.3            IF either test fails
                  Retire plant(s)
               ENDIF

C.1            IF future demand forecast exceeds capacity at t+2, .., t+5

                  FOR technology = 1 to 3
C.2                  Calculate NPV over next 20 periods of building plants
                     of sizes (Gap at t+2), (..), (Gap at t+5)
                  NEXT technology

C.3               Choose best option (highest forecast NPV)

               ENDIF

C.4            Rank all of this firm's existing plants in order of
               production cost per unit of output - renumber in descending
               order of cost

               FOR plant = 1 to "no. of plants owned by FIRM"

D.1               Calculate NPV of this single existing plant

D.2               Calculate future demand gap if firm retires all plants up
                  to and including this one for period (t+2), (..), (t+5)

                  FOR technology = 1 to 3

D.3                  Calculate NPV for building plants size (Gap at t+2),
                     (..), (Gap at t+5)

D.4                  Compare this NPV with the NPV of the plants which would
                     be retired to make these demand-capacity gaps

                  NEXT technology

               NEXT plant
```

```
E.1         Choose MAX of (all NPVs calculated above, 0)

E.2         Build the plant which has the largest NPV (or none, if no
            building project has positive expected NPV)

F.1         Re-appraise this firm's portfolio of three technologies

          NEXT firm

G.1       Allocate revenues and costs to Firms

G.2       Charge interest and Dividends to Firms as appropriate

G.3       Update Firms' demand forecasts

          FOR firm = 1 to "no. of firms"

H.1         Attempt innovation

          NEXT firm

        NEXT t

I.1     END
```

Appendix 8D: Previous versions of EMIR

EMIR is a complex simulation. It is important to be sure that it is working as intended. To this end, the model was developed in stages, adding sophistication as the more basic functions were seen to be correctly implemented.

The main stages of development, corresponding to different main versions of the model, were as follows:

VERSION	IMPORTANT FEATURES
1.0	Addition and retiring of units of capacity to meet demand
1.1	Forecasting of future demand levels
1.2	Price made a function of capacity utilisation
1.3	More complex decision rules introduced
1.39	Random order of firms' decision-making; perfect knowledge of competitor's planned changes in capacity once build-retire decision made
1.4	Model driven by command file; results saved to diskette data file
2.0	Simple incremental technological change
2.1	
2.2	Rationalisation of program structure, reduction in unnecessary array dimensions, to speed runs
2.3	Improved techological change (including imitation and scaleup)
3.0	Plural worldviews and strategies
3.1	Innovation and scaleup made dependent upon worldview
3.2	"Production" version further refined for automatic operation from batch file for multiple simulation runs

Appendix 8E: Debug Output

To assist in validating and verifying the correct operation of the model, "debug" statements are sent to the screen as the firms take decisions. At the end of each time-period the user may halt the simulation and interrogate the model about the state of the firms, plants and technologies at that time. These print statements (and others, since deleted) were used as successive versions of the model were developed to check that the program was operating as expected.

Inspection of the program printout will show that the following lines contain screen print statements:

File import:	1000	
Retiring of plants:	2180 2355	
Plant building plans:	3075 3250 3280 4060 4155 4283	4460 4605 4610 4617 4618 4885
General report each period:	5820 5830 5850 5860	
Option to inspect:	6000 - 6050 6200 - 6250 6300 - 6394 6400 - 6440	
Technological change:	9010 9040 9110 10110 10620	
Plant data error:	5283	

Other Checks on the Results

Further checks are made to validate the results of the simulation runs. Two data files are saved from each run. The first records (amongst other things) the total capacity and market price at the end of each period modelled. The other file saves details of all plants constructed during the run. Clearly, these variables saved on a period-by-period basis can be recalculated from the plant data. (Price is a function of production cost and capacity utilisation.) This is done by a separate program, which prints out the results of each run after performing such a reconciliation. This gives an extra assurance both that output data is saved correctly, and that it is properly calculated in the first place.

Appendix 8F: The EMIR Pricing Model

Economic theory often models demand as a function of price (at least for small, local changes). In EMIR we have deliberately made demand the crucial, exogenous parameter, so the conventional approach would not work.

The market price in EMIR is set according to the relationship:

$$\text{Price} = \text{Av. Production Cost} * (0.25 + \text{Demand} / \text{Capacity}) \qquad \text{(i)}$$

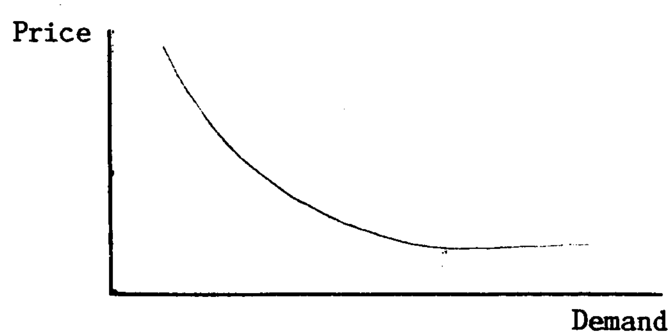
where "Av. Production Cost" is the weighted average of the production costs of all plants operating at that time, as defined in (34).

(i) says that, where total demand equals total supply and where all producers have the same costs, prices will be set to recover costs and earn a 25% return. Costs here include an 10% of construction costs - see equation (34). Assuming a 20-year plant life, half of this 10% per period is "depreciation", and the remainder represents financing costs. This is obviously crude in a number of ways, but has the merit of simplicity. Again, EMIR is not intended to be a detailed model of pricing strategy.

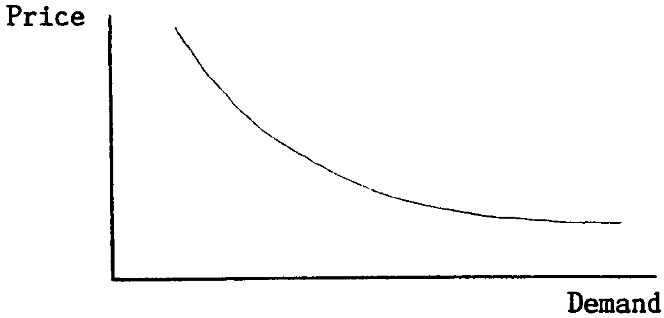
To see how (i) relates to the normal price model, consider a typical textbook relationship such as:

$$\text{Demand} = A * \text{Price}^{-B} \qquad \text{(ii)}$$

This implies that demand decreases as price increases:



In the case of (i), however, if we assume that capacity is unchanging in the short run (which it is in EMIR) we have an analogous position:



It can be seen that the relationships are qualitatively similar, but in EMIR price is driven by demand (in the short run), and in the usual microeconomic model demand is driven by price (again, in the short run).

Bidding and Marginal Plant Pricing

Equation (i) above says that when all producers have the same costs and demand exactly equals supply then the price will be set to make a 25% return on costs. However, it is unlikely that all producers will have identical costs. By setting prices as in (i), low-cost producers will earn higher profits, and high-cost plants will make smaller profits (or even losses).

Conventional theory states that prices should be set equal to the long-run marginal production cost. Another way of looking at the problem (of determining the industry price) is to consider it as a sort of reverse auction, in which producers offer to supply at fixed prices each period. Assuming (as is usually the case in EMIR) that total supply exceeds total industry demand, each producer has conflicting objectives in setting prices. A producer will wish to "bid" as high a price as possible for sale of his output. However, he will also wish to sell as much as he can. These two objectives resolve into the single objective of profit-maximisation. That is, we could assume that each producer strives to set prices to maximise sale proceeds each period.

However, there is another complication. Producers know that they are involved in a long-term struggle for survival and profit. After the present time period will come another - and performance then will depend upon the behaviour of competitors. There is an incentive for low-cost producers to set prices lower than they need in order to starve competitors of income, with the ultimate aim of putting them out of business.

Forces acting on the pricing decision act, therefore, in two directions. Encouraging firms to set prices high is:

- the desire to make large profit margins

Encouraging firms to set prices low is:

- the desire to sell as much as possible
- the desire to drive competitors out of business

There are clearly elements of game theory here; the price "bidding" would make an interesting simulation model in its own right.

It is assumed that (i) represents a fair compromise, indicating a sort of "centre of gravity" around which bids would be fixed. At this price level the "average" producer will make a reasonable return when capacity and demand are in balance. In real life it might well be that not all producers would set identical prices.

In summary, then, pricing is a very complex issue. A great deal more detail and complex could have been put into the model. This has not been done because price setting is not one of the important areas of enquiry for which the model was designed. The relationship (i) encapsulates reasonable assumptions, and is compatible with the traditional price-demand elasticity formulation.

Appendix 8G: Criteria for Rationalisation Projects

Some comments on section 5.4 of Chapter 8, which deals with how firms assess whether to build new plants in anticipation of retiring old and possibly less efficient ones, may be helpful.

Firms (in the real world) take decisions under conditions of uncertainty. Firms in EMIR are faced with uncertainty too - they have to forecast future demand, they are implicitly forecasting price by assuming that it will remain constant, they are faced with technological uncertainties, and they do not know how their competitors will behave.

Programming the model to allow the firms to make sophisticated forecasts of all these factors would be an interesting exercise, but would result in a simulation an order of magnitude more complex. Consequently, a heuristic approach is used. A simple set of decision rules is produced by using equations (47) to (50) in Chapter 8. The rules are designed to provide "reasonable" behaviour, allowing firms to invest in new capacity when appropriate, but not encouraging them to be too aggressive in the face of all their uncertainties.

The approach, as outlined in section 5.4, is:

A) Rank existing plants in order of their average production costs (as perceived by the firm - equation (2)).

Comment

This heuristically assumes that ordering by costs will give a correct ordering by NPV. This is almost, but not quite, always true. It could be untrue when a larger plant has slightly higher costs per unit of output than a smaller plant, but has a higher NPV due to greater expected sales. Due to the existence of economies of scale in fixed operating (Labour) costs, this happens rarely. (Only when the small plant has been the beneficiary of significant technological progress compared with the large plant.)

B) Consider the demand gap to be met in the future by subtracting the capacities of the firm's own plants, in order, from the available capacity.

<u>Comment</u>

This assumes that the less efficient (more expensive to run) plants actually will be retired. This is likely, but need not be the case.

C) Calculate the Net Present Value of each existing plant. Do this by assuming that all other plants owned by this firm which have higher average production costs have been retired.

<u>Comment</u>

As B) above. Note that the capital costs of existing plant are sunk, and do not have to be subtracted. The NPV is therefore the discounted value of the next 20 periods of operations. Note also that this makes the generous assumption that existing plants will actually last another 20 periods; they may have used up part or all of their "risk-free" 10 periods, so their expected remaining life could be as low as 10 more periods. (See Chapter 8, section 1.2.)

D) Calculate the NPV of the proposed new plant, of size defined in B) above, in this case allowing for the capital costs of construction. The criterion for accepting the project is then that its NPV is greater than the sum of the NPVs of the plants to be retired, each calculated as in C) above.

<u>Comment</u>

This is a strong condition to meet; the "true" expected NPV of the plants to be retired, considered together, is always less than the sum of the individual NPVs as calculated in C). This is because retiring the first plant increases the NPV of the second (by increasing its expected sales), etc. Imposing this rule means that there has to be a strong economic case for building plants based only or partly upon scrapping other capacity, rather than to meet forecast extra demand in the market.

It will be seen that the odds are weighted against rationalisation building; this is deliberate. In the face of the uncertainties mentioned above, firms should not be allowed to indulge in "kamikaze" construction projects. Nevertheless, in all simulation runs there are significant numbers of "rationalisation" plants built. These happen because old, small plants become relatively unprofitable, and hence have low NPVs. When a firm acquires a superior technology, plus the capability to build larger production units, the scope for a new, large and low-cost plant may be created.

One final comment: in order to partly redress the intentional stacking of the odds against "rationalisation" projects, a compensation has been made. Plant construction projects based on extra future demand may have been generated (see Chapter 8, section 5.3). Such projects have an NPV associated with them. Rationalisation projects, generated as above, will almost always have larger NPVs (because they will almost always be for larger plants - although the possibility that different technologies, and gaps from 2, 3, 4, or 5 years ahead, might have been used, means that this is not absolutely guaranteed). The best rationalisation project is then chosen in preference, without allowing for the NPV(s) of the plants assumed to be retired. However, examination of a few runs (using the screen output - see Appendix 8E) shows that in about 90% of all rationalisation builds, the decision would have been unchanged. The other 10% would have given marginally different conclusions. Given the weighting against rationalisations in all other respects, this is reasonable.

In conclusion, it should be re-emphasised that the approach taken is deliberately heuristic and not optimising. "Optimisation" would require price forecasting, more complex calculations of plant NPVs based upon expected lifetimes, calculation of NPV's which took account of retiring several simultaneously, and perhaps some forecasting of competitor behaviour too. The complexity of the model has to be cut off at some point, and section 5.4 represents a compromise between detail and pragmatism. It also gives sensible behaviour.

Appendix 8H: The Formulation of Technology in EMIR

Section 1.3 of Chapter 8 describes the modelling of technology in EMIR. This description is expanded here.

A technology in EMIR is defined by a quintuplet (K, L, V, MAX, MIN):

K	= Capital cost coefficient
L	= Labour " "
V	= Variable " "
MAX	= Maximum plant scale for which this technology is usable
MIN	= Minimum " " " " " " " "

A firm may build a plant of scale X. (X is measured in potential output - e.g. in tons/day. In the simulations, its value ranges from 40 to over 3000.) A plant of size X has the characteristics:

Scale lies between MIN and MAX

Capital construction cost	$= K * X^{0.7}$	(units - currency e.g. £)
Labour fixed cost	$= L * X^{0.4}$	(units - currency)
Variable cost per unit produced	$= V$	(units - currency)

The justification for these relationships is quoted in Chapter 8, and is derived from Chapter 2. The Capital and Labour cost relationships represent significant economies of scale. They resemble the familiar Cobb-Douglas production function formulation (Walters 1960, and Chapter 2 section 4.4). They are, however, based upon the specific cost-scale relationships empirically determined in the references quoted. Clearly, using these relationships is tantamount to adopting the "two-thirds power law", which was discussed in some detail in Chapter 2, section 5. It is a simplification with limitations; however, the model of technology is already complex enough, and could only be made more realistic by introducing detail in the fashion of Chapter 4. This was felt to be both infeasible and unnecessary.

Example

Consider a technology T in EMIR defined by the quintuplet

$$T - (K = 100,\ L = 50,\ V = 5,\ MAX = 400,\ MIN = 40)$$

With T we can construct a plant of scale X, where X is anywhere between 40 and 400 units of output per period. The capital construction cost of a plant scale X is

$$\text{Capital cost} = 100 * X^{0.7}$$

For example, a plant of scale 80 units output/period will cost

$$100 * 80^{0.7} = 100 * 21.486 = 2148.6 \text{ (£, say)}$$

The capital construction cost per unit capacity is thus

$$2148.6/80 = 26.86 \text{ per unit.}$$

Each period it operates, it will be charged a fixed overhead, and a variable production cost based upon its output. So if it produces 70 units the costs per period will be

$$\text{Overhead} = L * X^{0.4} = 50 * 80^{0.4} = 288.54$$

$$\text{Variable} = V * X = 5 * 70 = 350$$

This assumes less than full utilisation of the plant. The full overhead cost is charged for each period the plant is in operation, but the variable cost is charged only in proportion to the output actually achieved. It is assumed that the production process requires a fairly constant labour input (see Gold's (1981) comments on "capital-dominated" industries). Any other plant overheads are subsumed into the L coefficient. The variable costs represent energy costs, materials, any additional labour, etc.

Economies of Scale

Now if a plant of scale 200 were built using this technology, the capital construction cost would be

$$\text{Capital cost} = 100 * 200^{0.7} = 4080.6$$

The capital construction cost per unit of capacity would be

$$4080.6 / 200 = 20.40 \text{ per unit}$$

which is significantly lower than for the plant of scale 80 units output per period calculated above. A similar relationship (with even greater economies of scale) holds for the fixed overhead cost (based upon the L-relationship).

Appendix 8I: Forecasting Routines in EMIR

The forecasting used by firms in EMIR (see Chapter 8, section 4.1) is based upon Holt's method of exponentially-weighted moving averages. Let:

$m(t)$ = current estimate of level of demand

$b(t)$ = current estimate of rate of growth of demand

$y(t)$ = actual demand at time t

$Y(t)$ = forecast of demand at time t made at time t-1

Then:

$$e(t) = y(t) - Y(t) \tag{39}$$

$$m(t) = m(t-1) + b(t-1) + A1 * e(t) \tag{40}$$

$$b(t) = b(t-1) + A2 * e(t) \tag{41}$$

The forecast for k time periods ahead, made at time t, is given by:

$$Y(t,k) = m(t) + k * b(t) \tag{42}$$

In the simulation program, the forecasting routine is initialised by setting

$$m(0) = Y(1)$$

$$b(0) = (Y(10) - Y(1)) / 10$$

The parameters A1 and A2 affect the weightings given to past data. They depend upon the worldview of the forecasting firm, and the values used are:

Worldview	A1	A2
II	0.4	0.15
IV	0.2	0.08

I have tested these values for reasonableness in other forecasting applications. The implication of the values chosen is that II's take less account of past history than IV's, which latter tend to take a longer-term perspective to decision-making. (See also "J. Royal

Statistical Society" 1975, p.205.)

It is not claimed that this forecasting technique gives optimal results for any given demand series. (It could not be optimal for both world-views.) Its function is to introduce uncertainty into EMIR, whilst giving the simulated firms a plausible foundation on which to base capacity decisions. To the (inevitable) extent that forecasts are defective, the defects are shared by all firms in a particular scenario.

To gain an impression of how the forecasting model works, some results are given below, relating to the three demand series used in the runs described in Chapter 9. The five-period ahead forecasts are given, because those represent the maximum horizon firms look ahead to estimate a demand gap to be filled by constructing new capacity.

Note that the II-worldview tends to slightly superior performance, probably due to its quicker responses to changes in underlying trend in the demand series. The average absolute errors in the five-period ahead forecasts are respectable compared with (say) the five-year ahead forecasts of the C.E.G.B. from 1947 to 1970 (Abdulkarim and Lucas 1977), which made errors ranging from -11.3% to +28.8%.

DEMAND SERIES A

Forecast made at:	Five-period ahead forecast W'view II	W'view IV	Outcome
4	517	621	746
9	879	735	1173
14	1535	1398	1627
19	2261	2282	2298
24	2721	2830	2844
29	3200	3263	3049
34	3792	3722	3505
39	3972	3918	3812
44	3888	4052	3837
49	4205	4235	3920
54	4477	4352	4093
Av. abs. error	190	195	

DEMAND SERIES B

Forecast made at:	Five-period ahead forecast W'view II	W'view IV	Outcome
4	1035	1242	1491
9	1758	1471	2347
14	3070	2795	3253
19	4522	4564	4596
24	5442	5659	5687
29	6400	6525	6097
34	7584	7444	7009
39	7944	7835	7623
44	7775	8105	7674
49	8410	8471	7839
54	8954	8705	8187
Av. abs. error	380	391	

DEMAND SERIES C

Forecast made at:	Five-period ahead forecast W'view II	W'view IV	Outcome
4	1547	1616	1700
9	1789	1693	1986
14	2228	2136	2290
19	2715	2729	2740
24	3023	3096	3105
29	3344	3386	3243
34	3741	3694	3548
39	3861	3825	3754
44	3805	3915	3771
49	4017	4038	3826
54	4199	4116	3943
Av. abs. error	127	131	

Appendix 9A: Demand series and initial conditions for EMIR experiments

DEMAND SERIES

t	A	B	C
1	538.3	1076.7	1560.7
2	484.9	969.8	1524.9
3	479.3	958.6	1521.1
4	518.0	1036.0	1547.0
5	540.7	1081.3	1562.2
6	567.2	1134.5	1580.0
7	652.4	1304.8	1637.1
8	714.0	1427.9	1678.4
9	745.6	1491.3	1699.6
10	822.7	1645.5	1751.2
11	878.8	1757.5	1788.8
12	965.4	1930.8	1846.8
13	1096.9	2193.8	1934.9
14	1173.4	2346.7	1986.2
15	1304.4	2608.7	2073.9
16	1426.7	2853.4	2155.9
17	1432.8	2865.6	2160.0
18	1638.9	3277.9	2298.1
19	1626.5	3253.1	2289.8
20	1859.8	3719.7	2446.1
21	1927.8	3855.6	2491.6
22	1968.8	3937.6	2519.1
23	2108.6	4217.3	2612.8
24	2298.1	4596.2	2739.7
25	2366.6	4733.3	2785.6
26	2342.1	4684.2	2769.2
27	2645.0	5289.9	2972.1
28	2554.8	5109.6	2911.7
29	2843.6	5687.2	3105.2
30	2703.9	5407.7	3011.6
31	2998.6	5997.2	3209.1
32	2973.3	5946.7	3192.1
33	3216.0	6432.0	3354.7
34	3048.5	6097.0	3242.5
35	3193.7	6387.4	3339.8
36	3308.5	6617.1	3416.7
37	3337.4	6674.8	3436.0
38	3544.5	7088.9	3574.8
39	3504.7	7009.4	3548.1
40	3711.2	7422.4	3686.5
41	3664.8	7329.6	3655.4
42	3639.3	7278.5	3638.3
43	3602.2	7204.4	3613.5
44	3811.6	7623.3	3753.8
45	3798.0	7596.0	3744.7
46	4081.1	8162.2	3934.3
47	3887.6	7775.1	3804.7
48	3907.7	7815.4	3818.2
49	3836.8	7673.6	3770.7
50	3981.5	7962.9	3867.6
51	4090.8	8181.6	3940.8
52	4117.9	8235.8	3959.0
53	4202.4	8404.8	4015.6

54	3919.5	7839.1	3826.1
55	4148.2	8296.3	3979.3
56	4253.8	8507.6	4050.0
57	4202.6	8405.2	4015.7
58	4213.2	8426.5	4022.9
59	4093.3	8186.5	3942.5

Initial conditions

Initial conditions are completely defined by the starting state of the firms, all having initial Capital of 15,000 and Debt of 0. (See Chapter 8, section 7.1) These values are selected to allow firms to build several plants without encountering early gearing problems.

The demand series have different starting levels - B and C have higher opening demand than A. The number and capacity of plants owned by each firm for each series therefore varies, and varies further depending upon the number of firms modelled in the industry, as follows:

Table 9A.1: Initial number and size of Plants owned by each Firm for Simulations with each of the Demand Series

	Demand Series		
	A	B	C
4 firms	2 * 80	4 * 80	4 * 80
16 firms	1 * 40	1 * 80	1 * 80

It was desirable to have the same plant sizes for comparisons both between demand series, and between the 4 and 16 firm cases for the same demand series. This was not feasible without using all plants of scale 40, which would have led to too many small plants starting in runs with demand B and C. Table 9A.1 therefore represents a compromise.

There are four different opening configurations of technology, depending on whether High or Low capital intensity is simulated, and whether initial maximum plant scale is 100 or 400. The opening technological quintuplets (K, L, V, MAX, MIN) are therefore:

Table 9A.2: Initial Technological Coefficients

Capital Intensity	High		Low	
Maximum Scale	100	400	100	400
Coefficient K	100	100	50	50
L	50	50	50	50
V	5	5	5	5
MAX	100	400	100	400
MIN	40	40	40	40

See Chapter 8, section 1.3, for details of the model of production technology and the quintuplet (K, L, V, MAX, MIN). K relates to capital construction cost of the plant, L and V to its operating costs, and MAX and MIN to the size range within which it is feasible to construct the plant.

Appendix 9B: EMIR Results

The output measures (all taken at period t=59) used for comparison purposes are as follows. The headers from the data listing are given in brackets:

1. **Price** (PRICE): the market price for the output from plants. (Note that this is a function both of average production costs, and of capacity utilisation in the period in which it is measured).

2. **Average Production Cost** (PRODN COST): the average, weighted by plant scale, of the production cost for of all plants in the industry. Defined as in Chapter 8, section 1.2, equation (2).

3. **Lowest Production Cost** (BEST COST): the production cost, averaged over all of its plants, of the most efficient (i.e. lowest cost) firm.

4. **Number of firms Operating** (OP.): the number of non-bankrupt firms which are still actively operating at least one production plant.

5. **Number of firms Not Operating** (NOP.): the number of firms not operating any production plants, but who are not bankrupt.

6. **Number of firms Bankrupt** (BKPT): the number of firms driven out of business (see Chapter 8, section 3.5 for the conditions which produce bankruptcy).

7. **Top 25%** (TOP 25%): the proportion of the total production capacity held by the largest 25% of firms (i.e. by the biggest single firm in the 4-firm industries, by the biggest 4 firms in the 16-firm industries).

8. **Top 50%** (TOP 50%): as Top 25%, but for the largest 50% (2 or 8

firms).

9. **Largest Plant Scale** (MAXPLANT): the biggest plant which has been built in the industry up to that time (NB it does not have to be still operating).

10. **Average Plant Scale** (AV. PLANT): the average size of plant in existence at that time.

11. **Best K** (BEST K): the best (i.e. smallest) value of K (capital construction cost parameter) in a technology which has actually been used to construct a plant up to that time.

12. **Best L** (BEST L): as Best K, for Labour (fixed) cost technological parameter.

13. **Average K** (AVERAGE K): the average K value in all plants currently in operation.

14. **Average L** (AVERAGE L): as Average K, for L coefficient.

The run codes (see Ch 9, section 2.1) represent (4 or 16) firms, (high or low) capital intensity, (100 or 400) initial maximum plant scale, (ii or iv) worldview, (a, b or c) demand series ("n" representing no technical change, with demand series a) and (.1,2,3,4) random seed.

RUN	PRICE	PRODN COST	BEST COST	OP.	NOP.	BKPT	TOP 25%	TOP 50%
4hlivn.1	11.58	10.67	10.67	4	0	0	0.306	0.592
4hlivn.2	13.01	10.70	10.67	4	0	0	0.281	0.540
4hlivn.3	12.71	10.69	10.67	4	0	0	0.296	0.567
4hlivn.4	12.16	10.67	10.67	4	0	0	0.304	0.609
4hliin.1	14.36	10.75	10.67	4	0	0	0.308	0.554
4hliin.2	13.22	10.70	10.67	4	0	0	0.265	0.528
4hliin.3	13.07	10.76	10.67	4	0	0	0.292	0.571
4hliin.4	12.92	10.77	10.67	4	0	0	0.262	0.515

RUN	PRICE	PRODN COST	BEST COST	OP.	NOP.	BKPT	TOP 25%	TOP 50%
4h4ivn.1	8.81	8.24	8.03	3	0	1	0.550	0.950
4h4ivn.2	9.67	8.23	8.03	3	0	1	0.470	0.819
4h4ivn.3	10.74	8.10	8.03	3	0	1	0.597	0.805
4h4ivn.4	8.82	8.25	8.03	3	0	1	0.348	0.678
4h4iin.1	12.05	8.25	8.03	4	0	0	0.621	0.858
4h4iin.2	10.27	8.32	8.03	3	0	1	0.651	0.839
4h4iin.3	9.36	8.34	8.03	4	0	0	0.409	0.757
4h4iin.4	8.91	8.27	8.03	3	0	1	0.383	0.729
411ivn.1	10.95	9.49	9.41	4	0	0	0.300	0.536
411ivn.2	10.78	9.46	9.41	4	0	0	0.363	0.596
411ivn.3	10.75	9.45	9.41	4	0	0	0.317	0.612
411ivn.4	10.78	9.46	9.41	4	0	0	0.341	0.589
411iin.1	12.80	9.42	9.41	4	0	0	0.325	0.569
411iin.2	11.99	9.45	9.41	4	0	0	0.299	0.560
411iin.3	12.02	9.50	9.41	4	0	0	0.290	0.531
411iin.4	11.99	9.49	9.41	4	0	0	0.309	0.597
414ivn.1	7.74	7.24	7.20	2	0	2	0.920	1.000
414ivn.2	7.95	7.34	7.20	3	0	1	0.371	0.727
414ivn.3	9.04	7.27	7.20	3	0	1	0.461	0.806
414ivn.4	8.04	7.35	7.20	3	0	1	0.384	0.759
414iin.1	8.76	7.31	7.20	4	0	0	0.431	0.676
414iin.2	8.56	7.42	7.20	4	0	0	0.316	0.625
414iin.3	8.63	7.36	7.20	3	1	0	0.480	0.851
414iin.4	8.20	7.42	7.20	3	0	1	0.376	0.731
16h1iin.1	14.52	10.78	10.67	15	0	1	0.413	0.681
16h1iin.2	15.15	10.72	10.67	14	2	0	0.528	0.776
16h1iin.3	13.46	10.87	10.67	16	0	0	0.384	0.708
16h1iin.4	13.33	10.76	10.67	13	2	1	0.452	0.807
16h4ivn.1	9.95	8.28	8.03	9	3	4	0.705	1.000
16h4ivn.2	10.20	8.31	8.03	6	4	6	0.847	1.000
16h4ivn.3	10.09	8.11	8.03	8	4	4	0.842	1.000
16h4ivn.4	8.98	8.29	8.03	7	4	5	0.735	1.000
16h4iin.1	10.11	8.46	8.03	10	6	0	0.568	0.891
16h4iin.2	9.87	8.33	8.03	7	6	3	0.801	1.000
16h4iin.3	11.19	8.59	8.03	10	3	3	0.668	0.923
16h4iin.4	10.59	8.54	8.03	9	2	5	0.673	0.969
1611iin.1	12.27	9.54	9.41	14	2	0	0.506	0.792
1611iin.2	12.15	9.56	9.41	14	2	0	0.536	0.798
1611iin.3	11.68	9.55	9.41	16	0	0	0.456	0.720
1611iin.4	11.65	9.51	9.41	15	1	0	0.483	0.762
1614ivn.1	8.90	7.33	7.20	6	9	1	0.830	1.000
1614ivn.2	8.47	7.27	7.20	7	7	2	0.775	1.000
1614ivn.3	8.46	7.27	7.20	7	8	1	0.790	1.000
1614ivn.4	9.34	7.31	7.20	9	6	1	0.766	1.000

RUN	PRICE	PRODN COST	BEST COST	OP.	NOP.	BKPT	TOP 25%	TOP 50%
1614iin.1	9.04	7.41	7.20	6	9	1	0.900	1.000
1614iin.2	10.01	7.54	7.20	5	10	1	1.000	1.000
1614iin.3	8.95	7.47	7.20	7	9	0	0.803	1.000
1614iin.4	9.09	7.48	7.20	8	8	0	0.835	1.000
1611ivn.1	11.45	9.48	9.41	14	2	0	0.522	0.822
1611ivn.2	11.81	9.46	9.41	15	1	0	0.554	0.790
1611ivn.3	10.78	9.49	9.41	14	2	0	0.561	0.848
1611ivn.4	11.17	9.50	9.41	15	1	0	0.486	0.765
16hlivn.1	12.69	10.73	10.67	14	1	1	0.421	0.733
16hlivn.2	13.32	10.72	10.67	12	2	2	0.500	0.813
16hlivn.3	12.23	10.76	10.67	14	0	2	0.461	0.766
16hlivn.4	12.14	10.70	10.67	13	0	3	0.464	0.810
4hliva.1	7.09	7.13	6.38	3	0	1	0.885	0.949
4hliva.2	7.59	6.98	6.60	4	0	0	0.740	0.881
4hliva.3	7.87	7.27	6.49	1	1	2	1.000	1.000
4hliva.4	8.06	6.98	6.59	2	0	2	0.874	1.000
4hliia.1	8.51	7.37	6.63	4	0	0	0.501	0.792
4hliia.2	9.66	8.05	7.22	4	0	0	0.445	0.828
4hliia.3	7.61	7.24	6.53	3	1	0	0.724	0.924
4hliia.4	9.31	7.52	6.76	4	0	0	0.377	0.669
4h4iva.1	8.02	6.66	6.18	3	0	1	0.762	0.914
4h4iva.2	8.75	6.50	5.83	2	0	2	0.646	1.000
4h4iva.3	6.91	6.33	6.14	1	1	2	1.000	1.000
4h4iva.4	5.65	6.22	5.72	2	0	2	0.887	1.000
4h4iia.1	12.06	6.72	6.29	2	0	2	0.698	1.000
4h4iia.2	8.95	7.23	6.79	2	0	2	0.816	1.000
4h4iia.3	8.81	7.12	6.62	3	0	1	0.458	0.812
4h4iia.4	8.98	7.23	6.69	2	0	2	0.574	1.000
411iva.1	7.53	6.98	6.41	2	0	2	0.654	1.000
411iva.2	7.31	5.98	5.78	2	1	1	0.739	1.000
411iva.3	6.60	5.88	5.80	1	0	3	1.000	1.000
411iva.4	5.47	6.43	5.82	1	1	2	1.000	1.000
411iia.1	8.25	7.04	6.55	4	0	0	0.849	0.928
411iia.2	7.22	6.42	6.18	2	2	0	0.850	1.000
411iia.3	6.56	6.07	5.69	2	1	1	0.759	1.000
411iia.4	8.69	7.19	6.51	4	0	0	0.461	0.799
414iva.1	5.26	5.12	4.99	1	1	2	1.000	1.000
414iva.2	5.99	5.66	5.49	1	0	3	1.000	1.000
414iva.3	6.16	5.62	5.42	2	0	2	0.948	1.000
414iva.4	6.17	5.65	5.44	1	0	3	1.000	1.000
414iia.1	5.41	5.77	5.37	1	2	1	1.000	1.000
414iia.2	8.92	6.65	5.98	3	0	1	0.461	0.872
414iia.3	8.38	6.77	6.37	3	0	1	0.676	0.923
414iia.4	7.47	5.66	5.56	2	1	1	0.567	1.000

RUN	PRICE	PRODN COST	BEST COST	OP.	NOP.	BKPT	TOP 25%	TOP 50%
16hliva.1	8.59	7.02	6.54	2	7	7	1.000	1.000
16hliva.2	7.12	6.44	6.17	3	3	10	1.000	1.000
16hliva.3	7.75	7.07	6.61	3	5	8	1.000	1.000
16hliva.4	8.15	6.69	6.01	3	7	6	1.000	1.000
16hliia.1	10.05	8.94	7.57	9	7	0	0.748	0.983
16hliia.2	10.77	8.37	7.63	9	6	1	0.863	1.000
16hliia.3	8.63	7.27	6.59	6	9	1	0.883	1.000
16hliia.4	11.42	8.81	7.41	12	2	2	0.683	0.910
16h4iva.1	8.60	5.96	5.76	2	4	10	1.000	1.000
16h4iva.2	6.64	6.26	5.89	4	1	11	1.000	1.000
16h4iva.3	7.72	7.11	6.50	6	4	6	0.892	1.000
16h4iva.4	7.37	6.90	6.68	4	4	8	1.000	1.000
16h4iia.1	9.81	7.84	7.36	8	3	5	0.765	1.000
16h4iia.2	8.43	7.41	6.49	8	5	3	0.790	1.000
16h4iia.3	8.19	7.26	6.71	6	5	5	0.908	1.000
16h4iia.4	7.46	5.53	5.39	2	8	6	1.000	1.000
16lliva.1	5.57	5.11	5.06	1	9	6	1.000	1.000
16lliva.2	6.92	6.14	5.86	3	6	7	1.000	1.000
16lliva.3	6.73	6.16	5.99	2	7	7	1.000	1.000
16lliva.4	7.14	5.65	5.30	3	11	2	1.000	1.000
16lliia.1	6.45	5.90	5.68	2	13	1	1.000	1.000
16lliia.2	7.83	6.89	5.81	8	8	0	0.903	1.000
16lliia.3	9.05	7.49	6.54	7	7	2	0.930	1.000
16lliia.4	8.42	6.80	6.41	4	9	3	1.000	1.000
16l4iva.1	6.10	5.81	5.64	2	4	10	1.000	1.000
16l4iva.2	6.14	5.60	5.49	1	9	6	1.000	1.000
16l4iva.3	8.25	5.97	5.59	5	6	5	0.917	1.000
16l4iva.4	6.82	6.28	5.83	4	9	3	1.000	1.000
16l4iia.1	8.64	7.41	6.76	6	10	0	0.834	1.000
16l4iia.2	6.90	5.98	5.83	4	10	2	1.000	1.000
16l4iia.3	6.99	6.39	6.07	3	10	3	1.000	1.000
16l4iia.4	6.77	5.57	5.35	1	12	3	1.000	1.000
4hlivb.1	8.73	6.88	6.34	3	0	1	0.606	0.925
4hlivb.2	6.42	6.03	5.84	2	1	1	0.549	1.000
4hlivb.3	6.95	6.36	6.02	2	0	2	0.953	1.000
4hlivb.4	7.14	6.60	6.39	2	0	2	0.639	1.000
4hliib.1	10.02	7.93	7.45	4	0	0	0.338	0.639
4hliib.2	9.63	6.50	6.33	1	1	2	1.000	1.000
4hliib.3	7.06	6.15	5.49	4	0	0	0.789	0.884
4hliib.4	10.03	7.60	6.96	4	0	0	0.579	0.886
4h4ivb.1	6.44	5.78	5.62	1	0	3	1.000	1.000
4h4ivb.2	5.26	5.66	5.34	1	0	3	1.000	1.000
4h4ivb.3	7.99	6.50	6.06	3	0	1	0.516	0.837
4h4ivb.4	7.51	6.46	6.11	1	0	3	1.000	1.000

RUN	PRICE	PRODN COST	BEST COST	OP.	NOP.	BKPT	TOP 25%	TOP 50%
4h4iib.1	7.17	6.22	6.04	3	0	1	0.636	0.968
4h4iib.2	11.86	6.21	5.46	2	0	2	0.507	1.000
4h4iib.3	6.44	5.76	5.47	2	1	1	0.943	1.000
4h4iib.4	7.01	6.33	5.92	2	0	2	0.622	1.000
411ivb.1	6.01	5.52	5.22	1	0	3	1.000	1.000
411ivb.2	6.69	5.69	5.53	1	1	2	1.000	1.000
411ivb.3	7.37	7.24	6.31	3	0	1	0.490	0.831
411ivb.4	7.50	6.39	5.87	3	0	1	0.416	0.770
411iib.1	8.20	6.28	6.14	2	0	2	0.705	1.000
411iib.2	6.49	6.18	5.72	4	0	0	0.560	0.740
411iib.3	7.04	6.29	5.96	4	0	0	0.629	0.796
411iib.4	6.36	5.12	4.84	1	1	2	1.000	1.000
414ivb.1	6.39	5.91	5.56	1	0	3	1.000	1.000
414ivb.2	6.24	6.04	5.70	1	0	3	1.000	1.000
414ivb.3	6.20	5.71	5.34	2	0	2	0.514	1.000
414ivb.4	5.80	5.43	5.32	2	0	2	0.902	1.000
414iib.1	7.06	6.25	5.70	3	0	1	0.708	0.970
414iib.2	6.98	5.98	5.65	3	0	1	0.851	0.955
414iib.3	7.62	5.54	5.45	2	0	2	0.893	1.000
414iib.4	6.56	5.59	5.57	3	0	1	0.433	0.778
16hlivb.1	7.44	7.03	6.24	4	6	6	1.000	1.000
16hlivb.2	8.09	7.23	6.18	9	4	3	0.890	0.986
16hlivb.3	6.98	6.56	6.38	1	8	7	1.000	1.000
16hlivb.4	7.04	6.74	5.84	7	3	6	0.911	1.000
16hliib.1	9.38	7.98	7.18	14	1	1	0.636	0.860
16hliib.2	11.00	8.51	7.18	14	0	2	0.605	0.846
16hliib.3	9.95	7.18	6.23	11	3	2	0.753	0.974
16hliib.4	11.05	7.81	6.75	12	4	0	0.711	0.922
16h4ivb.1	8.33	6.58	6.10	5	4	7	0.954	1.000
16h4ivb.2	7.57	7.30	6.73	11	1	4	0.675	0.889
16h4ivb.3	8.02	6.84	6.42	6	0	10	0.871	1.000
16h4ivb.4	7.59	6.84	6.53	7	2	7	0.862	1.000
16h4iib.1	8.69	6.56	5.81	6	5	5	0.899	1.000
16h4iib.2	9.13	7.63	7.05	14	0	2	0.557	0.771
16h4iib.3	7.58	6.58	6.12	7	5	4	0.892	1.000
16h4iib.4	10.09	7.55	6.69	11	2	3	0.668	0.946
1611ivb.1	6.07	5.46	4.96	6	4	6	0.940	1.000
1611ivb.2	7.54	5.13	4.92	2	7	7	1.000	1.000
1611ivb.3	6.39	5.81	5.36	4	7	5	1.000	1.000
1611ivb.4	7.55	6.17	5.91	4	6	6	1.000	1.000
1611iib.1	6.39	5.43	5.36	2	12	2	1.000	1.000
1611iib.2	6.74	5.97	5.52	5	8	3	0.968	1.000
1611iib.3	14.59	5.61	5.41	1	13	2	1.000	1.000
1611iib.4	8.67	6.73	5.82	8	5	3	0.910	1.000

RUN	PRICE	PRODN COST	BEST COST	OP.	NOP.	BKPT	TOP 25%	TOP 50%
1614ivb.1	6.19	5.80	5.41	5	3	8	0.947	1.000
1614ivb.2	5.27	5.19	4.99	3	5	8	1.000	1.000
1614ivb.3	6.42	5.95	5.80	4	4	8	1.000	1.000
1614ivb.4	5.80	5.32	5.15	1	5	10	1.000	1.000
1614iib.1	8.65	5.59	5.51	1	12	3	1.000	1.000
1614iib.2	7.03	6.31	5.63	10	5	1	0.795	0.948
1614iib.3	6.58	5.63	5.39	2	11	3	1.000	1.000
1614iib.4	8.16	6.73	6.14	7	8	1	0.848	1.000
4h1ivc.1	7.28	6.61	6.37	1	3	0	1.000	1.000
4h1ivc.2	8.84	6.48	5.90	2	2	0	0.845	1.000
4h1ivc.3	7.31	7.19	6.64	4	0	0	0.718	0.893
4h1ivc.4	8.97	6.22	5.97	1	3	0	1.000	1.000
4h1iic.1	7.63	6.50	6.31	2	2	0	0.862	1.000
4h1iic.2	10.79	7.95	7.10	4	0	0	0.427	0.801
4h1iic.3	8.69	7.45	6.83	4	0	0	0.665	0.860
4h1iic.4	7.12	6.46	6.18	1	3	0	1.000	1.000
4h4ivc.1	8.32	6.70	6.23	3	0	1	0.603	0.827
4h4ivc.2	7.79	7.12	6.80	3	0	1	0.493	0.944
4h4ivc.3	6.00	5.53	5.49	1	2	1	1.000	1.000
4h4ivc.4	9.20	6.90	6.55	2	2	0	0.794	1.000
4h4iic.1	8.30	6.89	6.38	4	0	0	0.421	0.734
4h4iic.2	8.10	6.16	5.99	3	1	0	1.000	1.000
4h4iic.3	6.82	6.48	6.07	2	2	0	0.593	1.000
4h4iic.4	7.36	6.29	5.87	2	2	0	0.930	1.000
411ivc.1	8.10	6.25	5.77	2	0	2	0.756	1.000
411ivc.2	8.30	6.68	6.47	1	3	0	1.000	1.000
411ivc.3	6.43	5.51	5.23	1	3	0	1.000	1.000
411ivc.4	6.80	5.82	5.59	1	3	0	1.000	1.000
411iic.1	8.31	6.34	6.17	2	2	0	0.944	1.000
411iic.2	10.56	8.25	8.01	4	0	0	0.653	0.851
411iic.3	7.46	6.17	5.75	1	3	0	1.000	1.000
411iic.4	6.28	6.04	5.74	1	3	0	1.000	1.000
414ivc.1	6.45	5.90	5.73	2	1	1	0.771	1.000
414ivc.2	5.74	5.29	5.17	1	2	1	1.000	1.000
414ivc.3	6.04	5.54	5.48	1	2	1	1.000	1.000
414ivc.4	7.18	6.02	5.93	3	0	1	0.682	0.943
414iic.1	7.00	5.70	5.38	2	2	0	0.742	1.000
414iic.2	8.74	5.77	5.69	1	3	0	1.000	1.000
414iic.3	7.62	6.53	6.16	4	0	0	0.565	0.777
414iic.4	6.98	5.98	5.92	1	3	0	1.000	1.000
16h1ivc.1	8.89	7.89	7.26	8	8	0	0.724	1.000
16h1ivc.2	8.60	7.64	6.71	7	9	0	0.907	1.000
16h1ivc.3	10.03	7.84	6.86	7	9	0	0.770	1.000
16h1ivc.4	8.14	7.39	6.64	8	8	0	0.873	1.000

RUN	PRICE	PRODN COST	BEST COST	OP.	NOP.	BKPT	TOP 25%	TOP 50%
16h1iic.1	10.73	9.05	7.83	13	3	0	0.603	0.865
16h1iic.2	11.62	9.22	8.02	14	2	0	0.567	0.815
16h1iic.3	10.06	8.63	6.73	13	3	0	0.619	0.844
16h1iic.4	11.87	9.55	7.73	13	3	0	0.577	0.866
16h4ivc.1	6.49	6.17	5.88	3	9	4	1.000	1.000
16h4ivc.2	8.53	7.10	6.51	5	11	0	0.930	1.000
16h4ivc.3	8.53	6.79	6.32	3	12	1	1.000	1.000
16h4ivc.4	7.29	6.54	6.10	3	12	1	1.000	1.000
16h4iic.1	9.31	7.04	6.24	6	10	0	0.859	1.000
16h4iic.2	8.81	7.37	6.73	8	8	0	0.707	1.000
16h4iic.3	8.91	7.83	7.30	8	8	0	0.727	1.000
16h4iic.4	10.11	7.57	6.37	7	9	0	0.879	1.000
1611ivc.1	10.31	6.27	6.02	3	13	0	1.000	1.000
1611ivc.2	7.52	6.31	6.03	1	15	0	1.000	1.000
1611ivc.3	7.27	6.62	6.27	4	12	0	1.000	1.000
1611ivc.4	5.85	5.83	5.61	1	15	0	1.000	1.000
1611iic.1	7.53	6.35	5.94	4	12	0	1.000	1.000
1611iic.2	9.38	7.60	6.88	8	8	0	0.791	1.000
1611iic.3	9.47	8.12	7.13	13	3	0	0.619	0.893
1611iic.4	10.32	8.08	7.10	12	4	0	0.667	0.906
1614ivc.1	6.20	5.75	5.66	1	15	0	1.000	1.000
1614ivc.2	6.88	6.31	5.91	5	11	0	0.915	1.000
1614ivc.3	5.84	5.69	5.43	2	13	1	1.000	1.000
1614ivc.4	8.73	6.37	5.92	6	10	0	0.750	1.000
1614iic.1	7.58	6.35	5.97	4	12	0	1.000	1.000
1614iic.2	8.07	6.91	6.56	6	10	0	0.840	1.000
1614iic.3	5.32	5.30	5.06	1	15	0	1.000	1.000
1614iic.4	7.29	6.30	5.92	4	12	0	1.000	1.000

RUN	MAXPLANT	AV. PLANT	BEST K	BEST L	AVERAGE K	AVERAGE L
4h1ivn.1	100	100	100.00	50.00	100.00	50.00
4h1ivn.2	100	99	100.00	50.00	100.00	50.00
4h1ivn.3	100	99	100.00	50.00	100.00	50.00
4h1ivn.4	100	100	100.00	50.00	100.00	50.00
4h1iin.1	100	97	100.00	50.00	100.00	50.00
4h1iin.2	100	99	100.00	50.00	100.00	50.00
4h1iin.3	100	96	100.00	50.00	100.00	50.00
4h1iin.4	100	96	100.00	50.00	100.00	50.00
4h4ivn.1	400	333	100.00	50.00	100.00	50.00
4h4ivn.2	400	341	100.00	50.00	100.00	50.00
4h4ivn.3	400	380	100.00	50.00	100.00	50.00
4h4ivn.4	400	333	100.00	50.00	100.00	50.00

RUN	MAXPLANT	AV. PLANT	BEST K	BEST L	AVERAGE K	AVERAGE L
4h4iin.1	400	338	100.00	50.00	100.00	50.00
4h4iin.2	400	320	100.00	50.00	100.00	50.00
4h4iin.3	400	313	100.00	50.00	100.00	50.00
4h4iin.4	400	329	100.00	50.00	100.00	50.00
411ivn.1	100	96	50.00	50.00	50.00	50.00
411ivn.2	100	98	50.00	50.00	50.00	50.00
411ivn.3	100	98	50.00	50.00	50.00	50.00
411ivn.4	100	98	50.00	50.00	50.00	50.00
411iin.1	100	100	50.00	50.00	50.00	50.00
411iin.2	100	98	50.00	50.00	50.00	50.00
411iin.3	100	96	50.00	50.00	50.00	50.00
411iin.4	100	96	50.00	50.00	50.00	50.00
414ivn.1	400	385	50.00	50.00	50.00	50.00
414ivn.2	400	351	50.00	50.00	50.00	50.00
414ivn.3	400	375	50.00	50.00	50.00	50.00
414ivn.4	400	346	50.00	50.00	50.00	50.00
414iin.1	400	360	50.00	50.00	50.00	50.00
414iin.2	400	324	50.00	50.00	50.00	50.00
414iin.3	400	342	50.00	50.00	50.00	50.00
414iin.4	400	319	50.00	50.00	50.00	50.00
16h1iin.1	100	96	100.00	50.00	100.00	50.00
16h1iin.2	100	98	100.00	50.00	100.00	50.00
16h1iin.3	100	92	100.00	50.00	100.00	50.00
16h1iin.4	100	96	100.00	50.00	100.00	50.00
16h4ivn.1	400	331	100.00	50.00	100.00	50.00
16h4ivn.2	400	322	100.00	50.00	100.00	50.00
16h4ivn.3	400	375	100.00	50.00	100.00	50.00
16h4ivn.4	400	327	100.00	50.00	100.00	50.00
16h4iin.1	400	289	100.00	50.00	100.00	50.00
16h4iin.2	400	313	100.00	50.00	100.00	50.00
16h4iin.3	400	259	100.00	50.00	100.00	50.00
16h4iin.4	400	275	100.00	50.00	100.00	50.00
1611iin.1	100	94	50.00	50.00	50.00	50.00
1611iin.2	100	93	50.00	50.00	50.00	50.00
1611iin.3	100	94	50.00	50.00	50.00	50.00
1611iin.4	100	95	50.00	50.00	50.00	50.00
1614ivn.1	400	353	50.00	50.00	50.00	50.00
1614ivn.2	400	373	50.00	50.00	50.00	50.00
1614ivn.3	400	373	50.00	50.00	50.00	50.00
1614ivn.4	400	362	50.00	50.00	50.00	50.00
1614iin.1	400	325	50.00	50.00	50.00	50.00
1614iin.2	400	292	50.00	50.00	50.00	50.00
1614iin.3	400	309	50.00	50.00	50.00	50.00
1614iin.4	400	303	50.00	50.00	50.00	50.00

RUN	MAXPLANT	AV. PLANT	BEST K	BEST L	AVERAGE K	AVERAGE L
16llivn.1	100	97	50.00	50.00	50.00	50.00
16llivn.2	100	98	50.00	50.00	50.00	50.00
16llivn.3	100	96	50.00	50.00	50.00	50.00
16llivn.4	100	96	50.00	50.00	50.00	50.00
16hlivn.1	100	98	100.00	50.00	100.00	50.00
16hlivn.2	100	98	100.00	50.00	100.00	50.00
16hlivn.3	100	96	100.00	50.00	100.00	50.00
16hlivn.4	100	99	100.00	50.00	100.00	50.00
4hliva.1	1160	500	85.85	36.03	96.04	44.60
4hliva.2	730	445	64.49	34.17	76.75	35.42
4hliva.3	1180	447	95.43	26.91	104.67	27.71
4hliva.4	1100	503	85.06	23.16	95.75	28.60
4hliia.1	950	348	52.26	40.59	69.04	45.19
4hliia.2	620	308	65.82	44.19	91.18	48.65
4hliia.3	880	393	69.83	30.58	83.59	41.31
4hliia.4	820	318	48.27	41.56	69.54	50.25
4h4iva.1	810	536	74.12	22.08	86.36	26.92
4h4iva.2	1280	622	67.73	15.65	74.31	26.22
4h4iva.3	920	810	70.53	29.33	71.71	32.58
4h4iva.4	2150	889	74.12	22.16	88.51	26.22
4h4iia.1	920	442	33.29	34.78	40.88	36.96
4h4iia.2	890	518	78.51	41.99	88.91	43.48
4h4iia.3	640	415	50.25	34.79	64.10	44.58
4h4iia.4	690	413	66.29	45.61	69.11	50.27
41liva.1	540	260	42.03	24.23	48.10	27.53
41liva.2	1470	842	42.39	27.36	46.14	30.60
41liva.3	990	938	39.13	21.68	45.91	26.61
41liva.4	1780	682	46.12	46.50	49.75	47.48
41liia.1	870	370	41.46	35.26	48.25	48.43
41liia.2	880	585	37.97	39.22	47.31	40.39
41liia.3	1430	704	32.56	39.26	46.01	40.13
41liia.4	740	328	40.59	36.61	42.63	49.16
414iva.1	1620	1054	29.10	10.38	30.80	11.89
414iva.2	1180	845	32.82	17.06	35.32	19.42
414iva.3	890	605	35.91	12.17	41.70	12.45
414iva.4	1530	1215	45.38	20.93	47.64	25.27
414iia.1	1530	990	26.20	37.53	33.91	39.30
414iia.2	1070	375	24.29	36.57	37.53	40.58
414iia.3	880	376	28.41	39.12	33.40	42.41
414iia.4	870	638	29.26	31.70	31.65	33.33
16hliva.1	980	601	90.69	33.05	99.29	42.61
16hliva.2	820	598	67.27	21.89	75.81	27.09
16hliva.3	870	439	76.71	23.33	87.82	34.60
16hliva.4	1130	604	72.66	25.21	83.88	40.58

RUN	MAXPLANT	AV. PLANT	BEST K	BEST L	AVERAGE K	AVERAGE L
16hliia.1	250	151	53.77	37.49	80.18	46.50
16hliia.2	300	172	64.98	39.31	75.32	41.40
16hliia.3	410	273	39.88	29.86	57.54	37.25
16hliia.4	340	140	57.53	30.24	84.08	41.23
16h4iva.1	890	686	63.35	24.03	66.40	27.84
16h4iva.2	1100	561	56.84	17.65	76.54	24.26
16h4iva.3	900	377	69.52	25.31	78.09	32.47
16h4iva.4	760	500	73.21	24.06	82.85	33.41
16h4iia.1	420	292	52.34	41.95	74.44	47.63
16h4iia.2	730	329	49.59	32.19	71.22	39.56
16h4iia.3	670	358	49.83	36.12	55.97	40.07
16h4iia.4	1030	622	26.39	23.01	31.29	26.05
16lliva.1	1650	1623	23.87	24.80	24.24	30.02
16lliva.2	1420	778	41.82	31.84	55.19	34.66
16lliva.3	1540	972	42.70	27.21	51.48	44.15
16lliva.4	960	673	43.97	14.97	51.85	21.21
16lliia.1	840	608	33.07	34.41	33.39	35.94
16lliia.2	1020	201	24.63	26.27	36.04	35.19
16lliia.3	630	214	40.10	35.32	50.70	37.76
16lliia.4	760	376	39.60	40.39	41.06	42.94
1614iva.1	790	465	37.79	14.97	40.25	16.66
1614iva.2	2080	1208	33.94	20.12	37.43	22.72
1614iva.3	940	453	38.49	10.73	44.55	14.15
1614iva.4	770	445	45.25	15.24	48.00	23.52
1614iia.1	430	263	31.50	39.94	44.69	47.67
1614iia.2	840	566	27.75	28.50	32.04	29.28
1614iia.3	830	539	31.35	41.75	36.73	50.36
1614iia.4	1020	848	22.04	35.19	26.65	37.79
4hlivb.1	1700	730	91.10	41.64	97.02	44.86
4hlivb.2	3160	2010	89.92	29.44	98.32	39.34
4hlivb.3	1870	1215	84.11	44.32	88.36	44.95
4hlivb.4	1460	984	94.43	41.10	97.24	42.45
4hliib.1	560	351	74.56	46.86	85.60	51.34
4hliib.2	1910	1328	67.71	45.18	82.80	47.36
4hliib.3	2350	912	61.28	39.36	70.86	45.70
4hliib.4	1210	450	80.14	47.76	89.48	49.22
4h4ivb.1	2330	1578	82.66	23.19	87.07	24.34
4h4ivb.2	3570	2007	66.04	26.27	69.51	35.61
4h4ivb.3	1850	1045	69.01	30.71	87.87	39.92
4h4ivb.4	1600	997	63.20	30.87	75.26	35.43
4h4iib.1	1660	1134	41.02	34.90	57.42	42.08
4h4iib.2	2220	986	58.64	36.36	68.49	43.94
4h4iib.3	1690	1347	28.81	27.74	36.62	39.30
4h4iib.4	2330	1060	59.83	36.36	70.25	55.21

RUN	MAXPLANT	AV. PLANT	BEST K	BEST L	AVERAGE K	AVERAGE L
411ivb.1	3280	1627	44.33	44.25	45.34	44.36
411ivb.2	1540	1264	41.82	32.03	48.23	40.71
411ivb.3	940	296	44.64	35.10	46.92	44.68
411ivb.4	1400	682	47.52	40.09	52.95	46.50
411iib.1	1070	862	41.82	43.43	45.50	47.78
411iib.2	1290	683	29.13	46.23	36.66	47.98
411iib.3	1440	724	35.58	44.47	37.44	47.57
411iib.4	2250	1377	37.86	30.05	39.84	31.49
414ivb.1	2350	1096	41.42	21.59	57.75	30.70
414ivb.2	1160	803	47.43	31.45	53.56	35.31
414ivb.3	1550	817	24.28	23.51	39.06	30.41
414ivb.4	3110	2503	40.07	25.44	48.73	39.26
414iib.1	1610	775	35.30	42.32	44.28	47.02
414iib.2	1860	992	37.16	38.75	43.78	41.08
414iib.3	1810	1212	34.37	32.56	43.18	33.51
414iib.4	1970	1772	29.66	47.93	30.21	51.91
16h1ivb.1	2130	633	87.19	33.45	98.21	44.50
16h1ivb.2	1370	377	84.24	28.46	92.86	35.51
16h1ivb.3	1940	1439	77.03	35.05	98.28	40.59
16h1ivb.4	1790	490	66.33	17.22	82.67	30.25
16h1iib.1	500	221	49.84	32.90	70.36	43.77
16h1iib.2	420	191	52.94	37.50	80.00	46.98
16h1iib.3	730	327	59.67	31.44	73.54	39.94
16h1iib.4	770	270	52.82	34.22	77.08	46.35
16h4ivb.1	1390	806	63.09	36.62	77.36	41.53
16h4ivb.2	1010	433	77.22	25.03	87.83	35.51
16h4ivb.3	1470	682	75.32	32.32	88.64	37.63
16h4ivb.4	1520	680	80.99	28.13	91.79	33.30
16h4iib.1	1770	761	46.52	37.89	72.10	45.10
16h4iib.2	790	376	37.96	30.80	71.40	48.64
16h4iib.3	1380	698	55.26	38.24	65.76	41.15
16h4iib.4	430	314	50.74	33.84	76.90	42.15
1611ivb.1	2190	792	41.31	22.31	43.58	25.19
1611ivb.2	1910	1342	21.59	25.91	28.57	29.26
1611ivb.3	2320	689	38.26	21.83	48.31	26.86
1611ivb.4	1460	700	40.66	25.63	46.36	38.44
1611iib.1	1770	1472	21.95	40.11	26.81	47.94
1611iib.2	1510	621	25.97	27.75	34.39	31.64
1611iib.3	3130	1740	25.47	37.37	26.78	41.68
1611iib.4	1230	376	32.55	39.05	37.21	46.01
1614ivb.1	1930	910	36.04	21.46	43.07	25.14
1614ivb.2	2690	1783	32.44	21.28	38.40	25.31
1614ivb.3	1360	896	40.07	28.03	55.55	29.31
1614ivb.4	1880	1623	38.35	20.12	40.36	24.26

RUN	MAXPLANT	AV. PLANT	BEST K	BEST L	AVERAGE K	AVERAGE L
1614iib.1	2690	2103	31.45	40.10	37.40	48.22
1614iib.2	1570	526	22.52	31.95	40.71	39.32
1614iib.3	2660	1271	16.91	38.68	27.32	41.93
1614iib.4	880	447	30.42	37.17	39.70	47.78
4h1ivc.1	1710	1158	95.70	34.18	107.94	43.43
4h1ivc.2	1510	885	72.80	47.04	85.45	49.71
4h1ivc.3	1070	571	83.48	41.01	97.36	45.83
4h1ivc.4	1350	1103	82.21	32.26	88.10	39.57
4h1iic.1	1070	854	63.07	44.06	69.74	49.36
4h1iic.2	810	324	77.52	45.63	92.54	47.13
4h1iic.3	710	331	74.07	36.83	79.51	41.78
4h1iic.4	1330	926	58.88	34.49	75.41	42.62
4h4ivc.1	1240	569	68.93	27.15	82.69	31.80
4h4ivc.2	840	519	72.00	24.16	83.84	37.26
4h4ivc.3	1620	1577	48.46	34.03	49.32	35.70
4h4ivc.4	1030	607	60.23	22.37	85.34	37.20
4h4iic.1	730	344	57.39	30.53	59.74	32.38
4h4iic.2	1310	925	41.89	39.01	50.45	43.80
4h4iic.3	1240	818	51.64	37.93	58.16	45.17
4h4iic.4	1210	713	47.58	30.87	72.89	38.13
411ivc.1	1470	628	48.78	33.51	54.86	35.11
411ivc.2	690	567	45.00	37.50	47.01	45.31
411ivc.3	970	860	29.97	21.32	37.41	27.67
411ivc.4	860	858	34.44	34.29	40.02	38.95
411iic.1	810	620	40.72	40.90	44.67	42.77
411iic.2	220	167	39.51	36.84	48.17	46.78
411iic.3	1590	822	41.25	34.86	52.97	48.76
411iic.4	1170	713	23.79	37.62	31.03	40.77
414ivc.1	1330	778	45.04	18.29	52.11	21.89
414ivc.2	1240	944	24.84	12.19	29.73	14.82
414ivc.3	1360	1175	47.92	12.83	54.79	16.13
414ivc.4	750	523	39.56	18.99	45.19	22.12
414iic.1	790	576	15.39	35.17	21.31	38.86
414iic.2	1170	1040	33.07	30.46	34.56	31.30
414iic.3	860	430	26.48	31.90	38.03	40.33
414iic.4	1030	860	24.04	50.00	26.90	53.06
16h1ivc.1	460	300	87.83	22.94	99.48	35.24
16h1ivc.2	670	265	74.54	28.98	80.68	35.40
16h1ivc.3	600	239	77.73	23.82	92.09	33.16
16h1ivc.4	690	386	77.43	33.75	95.00	40.38
16h1iic.1	390	145	52.81	38.81	75.20	46.13
16h1iic.2	190	103	45.92	26.11	76.39	40.03
16h1iic.3	600	143	49.46	34.83	77.04	43.10
16h1iic.4	330	110	52.04	33.18	83.51	44.48

RUN	MAXPLANT	AV. PLANT	BEST K	BEST L	AVERAGE K	AVERAGE L
16h4ivc.1	1000	614	53.66	12.64	61.56	20.32
16h4ivc.2	910	518	76.60	31.21	91.34	37.36
16h4ivc.3	920	560	78.30	27.90	82.44	33.45
16h4ivc.4	760	507	47.66	25.38	63.52	30.00
16h4iic.1	890	335	52.64	30.14	61.99	33.11
16h4iic.2	550	298	61.81	37.92	69.45	42.53
16h4iic.3	420	261	44.47	26.90	75.67	41.38
16h4iic.4	910	279	49.03	35.07	65.53	44.74
1611ivc.1	990	566	39.63	26.81	46.49	31.14
1611ivc.2	1120	838	47.21	34.26	52.76	42.61
1611ivc.3	700	465	38.96	32.85	44.59	39.11
1611ivc.4	1430	1308	46.01	31.38	56.22	35.58
1611iic.1	800	526	28.82	37.59	36.28	45.16
1611iic.2	340	174	30.14	36.10	47.57	41.06
1611iic.3	230	148	32.41	35.45	43.16	44.63
1611iic.4	300	116	26.28	31.36	37.65	39.20
1614ivc.1	1130	952	47.03	20.59	50.86	23.74
1614ivc.2	900	426	35.17	27.66	40.64	30.68
1614ivc.3	1190	724	33.67	19.60	50.32	21.01
1614ivc.4	730	391	39.18	22.11	44.77	27.23
1614iic.1	840	523	23.03	36.48	35.48	45.61
1614iic.2	400	287	23.69	35.57	30.94	41.81
1614iic.3	1400	1046	20.49	38.03	24.56	41.86
1614iic.4	750	483	28.72	33.78	33.76	39.64

Appendix 9C: Regression Analysis of EMIR Results

The results obtained in section 2.5 of Chapter 9 have been based upon individual comparisons, with only one influence varying at a time. A more complex formulation should predict outcomes by considering the effects of the several factors varying together. This can be done by using multiple linear regression, with dummy (0/1) variables for each ot the experimental variables and demand series. A simple additive linear model is used; the objective is to confirm qualitative effects, not to find the ideal functional relationship between inputs and outputs.

Table 9C.1 reports the "best" equations derived by stepwise regression. It is a summary of the remainder of this Appendix. Each row gives the coefficients of the predictor variables (and constant) for the dependent variable (output measure), which is in the left-hand column.

Table 9C.1: Regression Analysis of Determinants of Industry Structure (Technical Change Runs)

N = 196

	Predictor Variable							
Output Measure (Dependent v'ble)	NFIRMS	CAPINS	MSIZE	WVIEW	DUM-B	DUM-C	CONSTANT	Adj. R^2
PCOST	0.3674	0.9155	-0.5379	-0.5405	-0.3610	-	6.600	54.56
TOP25	0.1160	-0.0956	-	0.1239	-	-	0.7629	27.44
AVPLANT	-220.4	-183.6	140.6	228.1	388.6	-	591.6	37.56
MAXPLANT	-280.7	-175.7	122.6	326.6	786.1	-	947.1	48.09
PR-OPS	-0.2005	0.1589	-0.0938	-0.2083	-	-	0.6289	39.16
PR-NOPS	0.2676	-0.1530	-	-	-0.0830	0.2383	0.2044	51.60
PR-BKPT	-0.0671	-	0.1152	0.2116	-	-0.2813	0.1934	62.38
BEST K	-4.563	29.935	-8.078	14.655	-	-	33.786	78.87
BEST L	-3.555	1.595	-4.728	-9.937	2.995	-	38.960	49.11

Key to Predictors:

NFIRMS	= 1 if 16 firms in simulation, 0 else
CAPINS	= 1 if Capital Intensity if High, 0 else
MSIZE	= 1 if initial max. plant size is 400, 0 else
WVIEW	= 1 if worldview is IV, 0 else
DUM-B	= 1 if demand series is B, 0 else
DUM-C	= 1 if demand series is C, 0 else

Key to Performance Measures (Dependent Variables):

PCOST	Average production cost
TOP25	Top quartile industry concentration
AVPLANT	Average plant size
MAXPLANT	Maximum plant size
PR-OPS	Proportion of firms still operating capacity
PR-NOPS	" " " not " "
PR-BKPT	" " " bankrupt
BEST K	Best (lowest) Capital coefficient discovered and used
BEST L	" " Labour " " " "

(All performance measures taken at t=59; see also Appendix 9B.)

Table 9C.1 presents results which are in close agreement with those found by examining single influences in section 2.5. Some of the R^2 values are disappointing; however, all reported coefficients are significant at least at the 5% level. The dummy variables for demand series do enter the regression equations in some cases, confirming that there are significant differences between results for some output measures. Again, the regression equations agree with the findings of section 2.5.3 above on this point.

It can therefore be concluded that the influences identified by looking at the effects of changing single experimental variables are preserved when we vary several factors simultaneously.

The full regression outputs are given below.

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2 LABEL: EMIR results 1990
NUMBER OF CASES: 192 NUMBER OF VARIABLES: 26

Experimental dummies as predictors of production cost

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: pcost

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 186)	PROB.	PARTIAL r-2
nfirms	.3674	.0846	18.874	.00002	.0921
capins	.9155	.0846	117.199	.00000	.3865
msize	-.5370	.0846	40.318	.00000	.1781
wview	-.5405	.0846	40.852	.00000	.1801
dum_b	-.3610	.0897	16.199	.00008	.0801
CONSTANT	6.6002				

STD. ERROR OF EST. = .5859

ADJUSTED R SQUARED = .5446
R SQUARED = .5566
MULTIPLE R = .7460

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	80.1369	5	16.0274	46.688	.000E+00
RESIDUAL	63.8508	186	.3433		
TOTAL	143.9876	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
dum_c	.0060	.7500	1.125	.2901

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2 LABEL: EMIR results 1990
NUMBER OF CASES: 192 NUMBER OF VARIABLES: 26

Predictors of top 25% concentration - all demand series

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: top25

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 188)	PROB.	PARTIAL r-2
nfirms	.1160	.0225	26.689	.00000	.1243
capins	-.0956	.0225	18.123	.00003	.0879
wview	.1239	.0225	30.434	.00000	.1393
CONSTANT	.7629				

STD. ERROR OF EST. = .1556

ADJUSTED R SQUARED = .2744
R SQUARED = .2858
MULTIPLE R = .5346

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	1.8220	3	.6073	25.082	4.000E-14
RESIDUAL	4.5522	188	.0242		
TOTAL	6.3742	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
msize	.0058	1.0000	1.100	.2956
dum_b	.0097	1.0000	1.829	.1779
dum_c	.0006	1.0000	.116	.7343

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2 LABEL: EMIR results 1990
NUMBER OF CASES: 192 NUMBER OF VARIABLES: 26

Predictors of average plant scale - all demand series

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: avplant

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 186)	PROB.	PARTIAL r-2
nfirms	-220.3958	49.0380	20.200	.00001	.0980
capins	-183.5417	49.0380	14.009	.00024	.0700
msize	140.6458	49.0380	8.226	.00461	.0424
wview	228.0625	49.0380	21.629	.00001	.1042
dum_b	388.6406	52.0126	55.831	.00000	.2309
CONSTANT	591.5990				

STD. ERROR OF EST. = 339.7450

ADJUSTED R SQUARED = .3756
R SQUARED = .3919
MULTIPLE R = .6261

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	13839108.6563	5	2767821.7313	23.979	6.000E-14
RESIDUAL	21469361.1562	186	115426.6729		
TOTAL	35308469.8125	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
dum_c	.0017	.7500	.318	.5734

---------------------- REGRESSION ANALYSIS ----------------------
HEADER DATA FOR: B:RES_Z2 LABEL: EMIR results 1990
NUMBER OF CASES: 192 NUMBER OF VARIABLES: 26

Predictors of maximum plant scale - all demand series

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: maxplant

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 186)	PROB.	PARTIAL r-2
nfirms	-280.7292	65.5049	18.367	.00003	.0899
capins	-175.7292	65.5049	7.197	.00796	.0373
msize	122.6042	65.5049	3.503	.06282	.0185
wview	326.5625	65.5049	24.853	.00000	.1179
dum_b	786.0938	69.4784	128.011	.00000	.4077
CONSTANT	947.0833				

STD. ERROR OF EST. = 453.8312

ADJUSTED R SQUARED = .4809
R SQUARED = .4945
MULTIPLE R = .7032

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	37471078.1250	5	7494215.6250	36.386	7.000E-14
RESIDUAL	38309079.6875	186	205962.7940		
TOTAL	75780157.8125	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
dum_c	.0025	.7500	.463	.4969

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2   LABEL: EMIR results 1990
NUMBER OF CASES: 192   NUMBER OF VARIABLES: 26

Predictors of proportion of firms still in business at t=59

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: pr-ops

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 187)	PROB.	PARTIAL r-2
nfirms	-.2005	.0304	43.382	.00000	.1883
capins	.1589	.0304	27.226	.00000	.1271
msize	-.0938	.0304	9.483	.00239	.0483
wview	-.2083	.0304	46.829	.00000	.2003
CONSTANT	.6289				

STD. ERROR OF EST. = .2109

ADJUSTED R SQUARED = .3916
R SQUARED = .4043
MULTIPLE R = .6359

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	5.6465	4	1.4116	31.730	.000E+00
RESIDUAL	8.3193	187	.0445		
TOTAL	13.9658	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
dum_b	.0086	1.0000	1.619	.2049
dum_c	.0000	1.0000	.002	.9640

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2   LABEL: EMIR results 1990
NUMBER OF CASES: 192   NUMBER OF VARIABLES: 26

Predictors of proportion of firms not in business at t=59

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: pr-nops

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 187)	PROB.	PARTIAL r-2
nfirms	.2676	.0285	87.883	.00000	.3197
capins	-.1530	.0285	28.731	.00000	.1332
dum_b	-.0830	.0350	5.638	.01858	.0293
dum_c	.2383	.0350	46.461	.00000	.1990
CONSTANT	.2044				

STD. ERROR OF EST. = .1978

ADJUSTED R SQUARED = .5160
R SQUARED = .5262
MULTIPLE R = .7254

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	8.1207	4	2.0302	51.915	.000E+00
RESIDUAL	7.3127	187	.0391		
TOTAL	15.4334	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
msize	.0030	1.0000	.565	.4531
wview	.0001	1.0000	.013	.9096

--------------------- REGRESSION ANALYSIS ---------------------

HEADER DATA FOR: B:RES_Z2   LABEL: EMIR results 1990
NUMBER OF CASES: 192   NUMBER OF VARIABLES: 26

Predictors of proportion bankrupt

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: pr-bkpt

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 187)	PROB.	PARTIAL r-2
nfirms	-.0671	.0204	10.856	.00118	.0549
msize	.1152	.0204	32.059	.00000	.1464
wview	.2116	.0204	108.087	.00000	.3663
dum_c	-.2813	.0216	169.755	.00000	.4758
CONSTANT	.1934				

STD. ERROR OF EST. = .1410

ADJUSTED R SQUARED = .6238
R SQUARED = .6317
MULTIPLE R = .7948

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	6.3772	4	1.5943	80.190	.000E+00
RESIDUAL	3.7179	187	.0199		
TOTAL	10.0950	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
capins	.0004	1.0000	.082	.7743
dum_b	.0064	.7500	1.205	.2738

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2   LABEL: EMIR results 1990
NUMBER OF CASES: 192   NUMBER OF VARIABLES: 26

Predictors of lowest (best) production cost

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: bppc

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 186)	PROB.	PARTIAL r-2
nfirms	.1819	.0653	7.764	.00588	.0401
capins	.6627	.0653	103.088	.00000	.3566
msize	-.3421	.0653	27.468	.00000	.1287
wview	-.3583	.0653	30.140	.00000	.1394
dum_b	-.3280	.0692	22.453	.00000	.1077
CONSTANT	6.1533				

STD. ERROR OF EST. = .4522

ADJUSTED R SQUARED = .4933
R SQUARED = .5065
MULTIPLE R = .7117

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	39.0404	5	7.8081	38.183	8.000E-14
RESIDUAL	38.0356	186	.2045		
TOTAL	77.0760	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
dum_c	.0078	.7500	1.458	.2288

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2 LABEL: EMIR results 1990
NUMBER OF CASES: 192 NUMBER OF VARIABLES: 26

Predictors of best (lowest) K value achieved

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: best k

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 187)	PROB.	PARTIAL r-2
nfirms	-4.5630	1.2919	12.475	.00052	.0625
capins	29.9347	1.2919	536.894	.00000	.7417
msize	-8.0780	1.2919	39.097	.00000	.1729
wview	14.6547	1.2919	128.674	.00000	.4076
CONSTANT	33.7857				

STD. ERROR OF EST. = 8.9506

ADJUSTED R SQUARED = .7887
R SQUARED = .7932
MULTIPLE R = .8906

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	57452.2061	4	14363.0515	179.285	.000E+00
RESIDUAL	14981.1118	187	80.1129		
TOTAL	72433.3179	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
dum_b	.0045	1.0000	.832	.3630
dum_c	.0034	1.0000	.634	.4268

REGRESSION ANALYSIS

HEADER DATA FOR: B:RES_Z2   LABEL: EMIR results 1990
NUMBER OF CASES: 192   NUMBER OF VARIABLES: 26

Predictors of best (lowest) L value achieved

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: best 1

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 186)	PROB.	PARTIAL r-2
nfirms	-3.5545	.8728	16.584	.00007	.0819
capins	1.5949	.8728	3.339	.06926	.0176
msize	-4.7280	.8728	29.343	.00000	.1363
wview	-9.9368	.8728	129.608	.00000	.4107
dum_b	2.9946	.9258	10.463	.00144	.0533
CONSTANT	38.9601				

STD. ERROR OF EST. = 6.0471

ADJUSTED R SQUARED = .4911
R SQUARED = .5044
MULTIPLE R = .7102

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	6923.6585	5	1384.7317	37.868	.000E+00
RESIDUAL	6801.6096	186	36.5678		
TOTAL	13725.2682	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
dum_c	.0144	.7500	2.700	.1020

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2 LABEL: EMIR results 1990
NUMBER OF CASES: 192 NUMBER OF VARIABLES: 26

Predictors of average K (capital) coefficient achieved

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: av k

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 188)	PROB.	PARTIAL r-2
capins	36.7124	1.3561	732.929	.00000	.7959
msize	-8.8980	1.3561	43.055	.00000	.1863
wview	11.3914	1.3561	70.565	.00000	.2729
CONSTANT	40.2440				

STD. ERROR OF EST. = 9.3951

ADJUSTED R SQUARED = .8154
R SQUARED = .8183
MULTIPLE R = .9046

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	74723.4112	3	24907.8037	282.183	1.700E-13
RESIDUAL	16594.4332	188	88.2683		
TOTAL	91317.8444	191			

VARIABLES NOT IN EQUATION:

NAME	PARTIAL r-2	TOLERANCE	F TO ENTER	PROB.
nfirms	.0051	1.0000	.968	.3265
dum_b	.0059	1.0000	1.112	.2929
dum_c	.0001	1.0000	.010	.9222

---------------------- REGRESSION ANALYSIS ----------------------

HEADER DATA FOR: B:RES_Z2   LABEL: EMIR results 1990
NUMBER OF CASES: 192   NUMBER OF VARIABLES: 26

Predictors of average L (labour) coefficient achieved

F TO ENTER = 3, F TO REMOVE = 3, TOLERANCE = .001

DEPENDENT VARIABLE: av 1

VAR.	REGRESSION COEFFICIENT	STD. ERROR	F(1, 185)	PROB.	PARTIAL r-2
nfirms	-2.0013	.8923	5.030	.02610	.0265
capins	3.5925	.8923	16.208	.00008	.0806
msize	-5.4927	.8923	37.888	.00000	.1700
wview	-10.3104	.8923	133.501	.00000	.4192
dum_b	4.8750	1.0929	19.897	.00001	.0971
dum_c	2.5917	1.0929	5.624	.01875	.0295
CONSTANT	42.2702				

STD. ERROR OF EST. = 6.1824

ADJUSTED R SQUARED = .5196
R SQUARED = .5347
MULTIPLE R = .7312

ANALYSIS OF VARIANCE TABLE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
REGRESSION	8124.0233	6	1354.0039	35.425	.000E+00
RESIDUAL	7070.9806	185	38.2215		
TOTAL	15195.0039	191			

---------------------- CORRELATION MATRIX ----------------------

HEADER DATA FOR: B:RES_Z1 LABEL: EMIR results 1990
NUMBER OF CASES: 192 NUMBER OF VARIABLES: 25

Industry structure variables - all demand series

	nfirms	capins	msize	wview	rseed	demser	price	pcost
nfirms	1.00000							
capins	.00000	1.00000						
msize	.00000	.00000	1.00000					
wview	.00000	.00000	.00000	1.00000				
rseed	.00000	.00000	.00000	.00000	1.00000			
demser	.00000	.00000	.00000	.00000	.00000	1.00000		
price	.18014	.39567	-.23468	-.41873	-.02228	.08892	1.00000	
pcost	.21213	.52860	-.31004	-.31208	.00024	.05178	.73376	1.00000
bppc	.14353	.52298	-.26996	-.28278	-.02669	.06212	.69873	.95538
top25	.31841	-.26238	.06463	.34002	.00648	-.02377	-.44491	-.51700
top50	.24038	-.16170	.18021	.29317	.00789	-.03233	-.31716	-.43271
maxplant	-.22342	-.13986	.09758	.25990	-.02703	-.03554	-.43962	-.63963
avplant	-.25697	-.21400	.16399	.26591	-.00728	.03231	-.50498	-.73394
best k	-.11746	.77059	-.20795	.37725	-.00995	-.01310	.20534	.39936
best 1	-.21020	.09432	-.27960	-.58763	-.02822	.08443	.31938	.29446
av k	-.03059	.84170	-.20400	.26117	.00113	.01541	.32782	.55824
av 1	-.11248	.20191	-.30871	-.57949	.03375	.11894	.40897	.44384
pr-ops	-.37175	.29450	-.17380	-.38623	-.02375	.04435	.42276	.58073
pr-nops	.47189	-.26982	-.03789	-.00574	.04467	.34311	-.10734	-.22988
pr-bkpt	-.14622	-.01278	.25127	.46138	-.02730	-.47640	-.36453	-.39881

	bppc	top25	top50	maxplant	avplant	best k	best 1	av k
bppc	1.00000							
top25	-.49409	1.00000						
top50	-.41951	.76203	1.00000					
maxplant	-.66730	.27473	.23916	1.00000				
avplant	-.68099	.36340	.29233	.85698	1.00000			
best k	.42984	-.14018	-.06075	.00100	-.09725	1.00000		
best 1	.31638	-.32953	-.31344	-.03861	-.06051	.03020	1.00000	
av k	.56197	-.22715	-.14030	-.09199	-.20927	.94914	.04744	1.00000
av 1	.44880	-.39663	-.35989	-.08032	-.12453	.08966	.90469	.16123
pr-ops	.54984	-.83983	-.78361	-.31253	-.43948	.17845	.36313	.27391
pr-nops	-.21577	.58494	.48586	-.08289	.07633	-.27936	-.07227	-.29508
pr-bkpt	-.37994	.26455	.32093	.47009	.42254	.13551	-.33775	.04268

	av 1	pr-ops	pr-nops	pr-bkpt
av 1	1.00000			
pr-ops	.41908	1.00000		
pr-nops	-.07937	-.65744	1.00000	
pr-bkpt	-.39478	-.36330	-.46317	1.00000

CRITICAL VALUE (1-TAIL, .05) = + Or - .11910
CRITICAL VALUE (2-tail, .05) = +/- .14164

N = 192

Appendix 9D: EMIR Simulation Results Summary

METHODOLOGY FOR COMPARISON

The effects of each experimental factor are assessed by pairing up simulation runs. The pairings are arranged such that only the single factor under scrutiny differs between the runs. For example, suppose the factor for analysis were worldview. The run 4H1IVA.1 would be paired with 4H1IIA.1 (the ".1" denoting that the run was performed with random number seed = 1), 16L4IVB.2 with 16L4IIB.2, 16H1IVC.3 with 16H1IIC.3, etc.

For a full analysis over all three demand series and four random number streams, the "technical change" runs allow a total of 96 comparisons for each factor, whilst the "no technical change" runs permit 32 comparisons to be made.

STATISTICAL SIGNIFICANCE

Having made the pairings, it is possible to perform a simple statistical test on the results to assess the significance of the experimental variables. For example, for comparing average plant scale at the end of the simulations, the sign of the difference (+ or -) between plant sizes at t=59 would be noted for the 96 pairings. The 96 + and - differences can then be tested against the hypothesis that there is no difference between average plant scale for runs with worldview IV and worldview II (for example). Cases when the results are equal i.e. the difference is 0, are discarded, leaving fewer pairings.

The null hypothesis is that there are equal numbers of + and - differences; this is tested by using the Normal approximation to the Binomial distribution. We assume that the probability of a + difference is p = 0.5. The probability of a - difference is then 1-p = 0.5 also. If there are n trials, we can approximate the Binomial with the Normal distribution, with

$$\text{Mean} = n * p$$

and

$$\text{Variance} = n * p * (1-p)$$

provided that $n * p$ and $n * (1-p)$ are both greater than 5. In these cases $p = 1-p = 0.5$, and n is normally (much) greater than 20, so these conditions hold. (In cases where n is less than 10, the probabilities can be calculated exactly without the Normal approximation.)

Since we are testing the hypothesis that "there is no difference", a two-tailed test is employed. Confidence intervals are therefore drawn by looking at intervals representing 1.96 standard deviations (5% level), 2.576 s.d.'s (1%) and 3.29 s.d.'s (0.1%) from the mean. A "continuity correction" must be made (to allow for the fact that scores can only be integers i.e. a score of 40 is equivalent to the range $39\frac{1}{2}$ to $40\frac{1}{2}$ on the continuous Normal distribution). The following table gives the "critical" results at 5%, 1% and 0.1% significance levels for various values of n:

			Significance Level		
n	mean	s.d.	5%	1%	0.1%
32	16	2.828	(22 , 10)	(24 , 8)	(26 , 6)
48	24	3.464	(31 , 17)	(33 , 15)	(36 , 12)
64	32	4.000	(40 , 24)	(43 , 21)	(46 , 18)
96	48	4.899	(58 , 38)	(61 , 35)	(65 , 31)

The above table shows, for given n and significance level, the scores required to disprove the null hypothesis. In the tables of results below, 1 "point" is awarded for a positive difference.

The comparisons are tabulated below. They are based on the same output measures, in the same order, as listed at the beginning of Appendix 9B. The entries count the number of times the given measure was larger for each of the experimental influences. Thus, for the runs with no technical change (see first line of first table below), the market price at t=59 was higher for simulation runs with worldview II on 28 occasions, and higher for runs with worldview IV 4 times.

Note that not all rows add up to 32 (or 64, or 96). This is because comparisons where the outcome was identical are ignored. (For example, for the "no technical change" runs no non-zero comparisons are made on the technical change measures.)

RUNS WITH NO TECHNICAL CHANGE

Comparisons at t=59 (no technical change)

Compared on **WORLDVIEWS** -	II : IV
Price	28 : 4 ***
Average prodn cost	28 : 2 ***
Lowest prodn cost	0 : 0
Proportion of firms:	
Operating	12 : 3 *
Not Operating	8 : 4
Bankrupt	0 : 14 ***
Market share of:	
Top 25%	11 : 21
Top 50%	7 : 20 *
Plant scale:	
Largest	0 : 0
Average	2 : 27 ***
Technology:	
Best K	0 : 0
Best L	0 : 0
Average K	0 : 0
Average L	0 : 0

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Comparisons at t=59 (no technical change)

Compared on **NO. FIRMS** - 4 : 16

Price	9 : 23 *
Average prodn cost	4 : 26 ***
Lowest prodn cost	0 : 0
Proportion of firms:	
Operating	30 : 0 ***
Not Operating	0 : 27 ***
Bankrupt	6 : 12
Market share of:	
Top 25%	2 : 30 ***
Top 50%	0 : 31 ***
Plant scale:	
Largest	0 : 0
Average	27 : 3 ***
Technology:	
Best K	0 : 0
Best L	0 : 0
Average K	0 : 0
Average L	0 : 0

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Comparisons at t=59 (no technical change)

Compared on **MAX PLANT** - 100 : 400

Price	32 : 0 ***
Average prodn cost	32 : 0 ***
Lowest prodn cost	32 : 0 ***
Proportion of firms:	
Operating	28 : 0 ***
Not Operating	0 : 16 ***
Bankrupt	1 : 24 ***
Market share of:	
Top 25%	0 : 32 ***
Top 50%	0 : 32 ***
Plant scale:	
Largest	0 : 32 ***
Average	0 : 32 ***
Technology:	
Best K	0 : 0
Best L	0 : 0
Average K	0 : 0
Average L	0 : 0

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Comparisons at t=59 (no technical change)

Compared on **CAP INTENSITY** - Low : High

Price	2 : 30 ***
Average prodn cost	0 : 32 ***
Lowest prodn cost	0 : 32 ***
Proportion of firms:	
Operating	6 : 9
Not Operating	13 : 2 **
Bankrupt	2 : 14 **
Market share of:	
Top 25%	23 : 9 *
Top 50%	18 : 9
Plant scale:	
Largest	0 : 0
Average	14 : 14
Technology:	
Best K	0 : 32 ***
Best L	0 : 0
Average K	0 : 32 ***
Average L	0 : 0

* = significant at 5% level; ** = 1% level; *** = 0.1% level

COMPARISON BETWEEN RUNS WITHOUT AND WITH TECHNICAL CHANGE

Comparisons at t=59

	Tech Change : No Tech Change
Price	3 : 61 ***
Average prodn cost	0 : 63 ***
Lowest prodn cost	0 : 64 ***
Proportion of firms:	
Operating	1 : 54 ***
Not Operating	33 : 6 ***
Bankrupt	49 : 2 ***
Market share of:	
Top 25%	61 : 2 ***
Top 50%	49 : 1 ***
Plant scale:	
Largest	64 : 0 ***
Average	63 : 1 ***
Technology:	
Best K	5 : 59 ***
Best L	3 : 61 ***
Average K	0 : 64 ***
Average L	0 : 64 ***

* = significant at 5% level; ** = 1% level; *** = 0.1% level

RUNS WITH TECHNICAL CHANGE

Comparisons at t=59

DEMAND SERIES	A	B	C	TOTAL	
Compared on **WORLDVIEW**	II : IV	II : IV	II : IV	II : IV	
Price	27 : 5	25 : 7	24 : 8	76 : 20	***
Average prodn cost	29 : 3	19 : 13	25 : 7	73 : 23	***
Lowest prodn cost	27 : 5	21 : 11	23 : 8	71 : 24	***
Proportion of firms:					
Operating	22 : 4	24 : 7	20 : 3	66 : 14	***
Not Operating	15 : 5	11 : 6	8 : 17	34 : 28	
Bankrupt	2 : 26	2 : 28	0 : 12	4 : 66	***
Market share of:					
Top 25%	5 : 21	8 : 22	5 : 20	18 : 63	***
Top 50%	1 : 11	2 : 16	2 : 11	5 : 38	***
Plant scale:					
Largest	5 : 27	10 : 22	8 : 23	23 : 72	***
Average	4 : 28	11 : 21	6 : 26	21 : 75	***
Technology:					
Best K	11 : 21	4 : 28	7 : 25	22 : 74	***
Best L	30 : 2	28 : 4	29 : 3	87 : 9	***
Average K	3 : 29	2 : 30	5 : 27	10 : 86	***
Average L	29 : 3	26 : 6	25 : 7	80 : 16	***

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Comparisons at t=59

DEMAND SERIES	A	B	C	TOTAL	
Compared on **NO. FIRMS**	4 : 16	4 : 16	4 : 16	4 : 16	
Price	14 : 18	9 : 22	12 : 20	35 : 60	*
Average prodn cost	15 : 17	11 : 21	7 : 25	33 : 63	**
Lowest prodn cost	13 : 18	17 : 15	12 : 19	42 : 52	
Proportion of firms:					
Operating	26 : 2	22 : 10	21 : 8	69 : 20	***
Not Operating	0 : 29	1 : 28	7 : 22	8 : 79	***
Bankrupt	16 : 12	19 : 10	7 : 1	42 : 23	*
Market share of:					
Top 25%	4 : 22	10 : 20	11 : 15	25 : 57	***
Top 50%	0 : 12	6 : 12	5 : 8	11 : 32	**
Plant scale:					
Largest	20 : 12	19 : 13	25 : 7	64 : 32	**
Average	19 : 13	22 : 10	26 : 6	67 : 29	***
Technology:					
Best K	16 : 16	19 : 13	17 : 15	52 : 44	
Best L	17 : 15	24 : 8	17 : 15	58 : 38	*
Average K	19 : 13	25 : 7	19 : 13	63 : 33	**
Average L	17 : 15	25 : 7	19 : 13	61 : 35	**

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Comparisons at t=59

DEMAND SERIES	A	B	C	TOTAL
Compared on **PLANT SIZE**	100 : 400	100 : 400	100 : 400	100 : 400
Price	21 : 11	18 : 14	23 : 9	62 : 34 **
Average prodn cost	25 : 7	18 : 13	22 : 8	65 : 28 ***
Lowest prodn cost	24 : 8	19 : 13	22 : 10	65 : 31 ***
Proportion of firms:				
Operating	15 : 10	17 : 20	17 : 9	49 : 29 *
Not Operating	16 : 8	15 : 4	11 : 8	42 : 30
Bankrupt	5 : 21	5 : 24	1 : 10	11 : 55 ***
Market share of:				
Top 25%	10 : 13	11 : 14	11 : 15	32 : 42
Top 50%	4 : 8	6 : 11	5 : 10	15 : 29 *
Plant scale:				
Largest	16 : 16	14 : 18	13 : 19	43 : 53
Average	10 : 22	9 : 23	11 : 21	30 : 66 ***
Technology:				
Best K	29 : 3	20 : 12	27 : 5	76 : 20 ***
Best L	22 : 10	20 : 11	23 : 9	65 : 30 ***
Average K	24 : 8	26 : 6	24 : 8	74 : 22 ***
Average L	21 : 11	24 : 8	24 : 8	69 : 27 ***

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Comparisons at t=59

DEMAND SERIES	A	B	C	TOTAL
Comparedon **CAPITAL INTENSITY**	Low : High	Low : High	Low :High	Low : High
Price	4 : 28	7 : 25	7 : 25	18 : 78 ***
Average prodn cost	2 : 30	5 : 27	4 : 28	11 : 85 ***
Lowest prodn cost	1 : 31	5 : 27	5 : 27	11 : 85 ***
Proportion of firms:				
Operating	3 : 20	8 : 18	4 : 21	15 : 59 ***
Not Operating	20 : 3	14 : 5	21 : 4	55 : 12 ***
Bankrupt	10 : 15	13 : 12	2 : 2	25 : 29
Market share of:				
Top 25%	18 : 5	19 : 10	20 : 5	57 : 20 ***
Top 50%	10 : 1	13 : 6	10 : 2	33 : 9 ***
Plant scale:				
Largest	22 : 10	20 : 12	13 : 19	55 : 41
Average	24 : 8	21 : 11	20 : 12	65 : 31 ***
Technology:				
Best K	0 : 32	1 : 31	1 : 31	2 : 94 ***
Best L	10 : 22	13 : 19	10 : 22	33 : 63 **
Average K	1 : 31	1 : 31	0 : 32	2 : 94 ***
Average L	12 : 20	17 : 15	12 : 20	41 : 55

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Appendix 9E: Comparison of output measures between runs with demand series A, B and C

A casual inspection of the latter four tables of Appendix D shows that the results for each of the three demand series demonstrate the same qualitative effects for the input experimental variables. In only four cases out of the 56 does a result for one demand series indicate an influence in one direction while the other two suggest the opposite. Moreover, in only one of these four cases are the results for any single demand series statistically significant anyway.

The conclusion that there is no difference between the effects of the experimental influences on the outcome variables for the three demand series can be considerably strengthened by showing that, in the majority of cases, there are no significant differences between the numerical counts from the non-parametric tests of Appendix D for the three demand series.

There are 32 paired comparisons for each demand series with technical change allowed, a total of 96 in all (Appendix D). Suppose that the observed frequencies of an output measure (e.g. "plant scales are larger") for a given input variable (e.g. "worldview = IV") are P_A, P_B, and P_C respectively for demand series A, B and C. Suppose also that the observed frequencies of the opposite result (e.g. "plant scales are smaller") are Q_A, Q_B and Q_C. Then we can test the observed frequencies against the null hypothesis that they are all drawn from the same population,

There are six categories for which we have expected and observed frequencies. A Chi-quared goodness-of-fit test can be carried out to test the assumption that there is no significant difference between the results for the three demand series A, B and C. Defining:

$$P = (P_A + P_B + P_C)$$

$$Q = Q_A + Q_B + Q_C$$

we will expect to observe the following proportions E, on the assumption that there is no difference between the three demand series:

(series A:) $E_A = P * (P_A + Q_A) / (P + Q)$

- and similarly for demand series B and C, and for the proportions of "non-occurences" (Q's), etc.

For example, consider the runs with technical change, output measure 'Price at t=59', compared on worldview II vs. worldview IV (see Appendix 9D). For demand series A the II's have higher prices at t=59 in 27 out of 32 cases. For B the II's are higher in 25 out of 32, and for C they are higher in 24 out of 32. Is the difference significant?

The expected number of higher cases is (27 + 25 + 24) * 32/96 = 25.333. The expected number of lower cases is (5 + 7 + 8) * 32/96 = 6.667. Then the situation is as follows:

CASE	EXPECTED FREQUENCY	OBSERVED FREQUENCY	$(O - E)^2 / E$
A higher	25.333	27	0.110
A lower	6.667	5	0.417
B higher	25.333	25	0.004
B lower	6.667	7	0.017
C higher	25.333	24	0.070
C lower	6.667	8	0.267
	Sum of squared differences =		0.885

So long as the expected frequency cells all exceed 5, the sum of squared differences will follow a Chi-squared distribution with 2 degrees of freedom. 0.885 lies between the 70% and 50% points of that distribution, so there is no reason to conclude that there is any difference between the results for the three demand series on this measure.

This calculation was applied to all of the results listed for three demand series in Appendix 9D. There are 56 sets of paired comparisons (14 output measures compared for 4 input influences). Of these 56 sets, 19 could not be tested by using the Chi-squared because the procedure outlined above yielded classes with fewer than five expected observations. Of the 37 remaining testable sets, 2 were found which exceeded the 5% point of the Chi-squared distribution; one exceeded the 1% point. However, 2 out of 40 would be expected to fail at the 5% significance level by chance alone; 1 or more out of 37 would fail at the 1% level about one time in three by pure chance alone. This finding is therefore not remarkable. Hence we can reasonably conclude that there is no important difference between the results for the three demand series.

(The reader may be concerned that the 19 cases which could not be formally tested in this way may hide the exceptions. He or she is invited to study Appendix 9D briefly again. For example, see the comparisons on "Worldview"; the proportions for 'Bankrupt' are 2:26, 2:28, 0:12. Those for 'Top 50%' are 1:11, 2:16, 2:11. For 'Best L' 30:2, 28:4, 29:3. For 'Average K' they are 3:29, 2:30, 5:27. For 'Average L' 29:3, 26:6, 25:7. Etcetera.)

Appendix 9F: Comparison of EMIR Output Measures By Demand Series

Performance measures and method of comparison are as in Appendix 9D.

Comparisons at t=59

Demand series -	A : B
Price	34 : 30
Average prodn cost	42 : 22 *
Lowest prodn cost	46 : 18 ***
Proportion of firms:	
Operating	20 : 31
Not Operating	28 : 12 *
Bankrupt	20 : 22
Market share of:	
Top 25%	34 : 19 *
Top 50%	19 : 10
Plant scale:	
Largest	8 : 56 ***
Average	11 : 51 ***
Technology:	
Best K	29 : 35
Best L	17 : 47 ***
Average K	33 : 31
Average L	17 : 47 ***

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Comparisons at t=59

Demand series -	A : C
Price	24 : 40 *
Average prodn cost	29 : 35
Lowest prodn cost	24 : 40 *
Proportion of firms:	
Operating	22 : 31
Not Operating	9 : 43 ***
Bankrupt	51 : 0 ***
Market share of:	
Top 25%	30 : 20
Top 50%	15 : 8
Plant scale:	
Largest	35 : 28
Average	33 : 31
Technology:	
Best K	31 : 33
Best L	25 : 39
Average K	32 : 32
Average L	23 : 41 *

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Comparisons at t=59

Demand series -	B : C
Price	21 : 42 **
Average prodn cost	25 : 39
Lowest prodn cost	20 : 44 **
Proportion of firms:	
Operating	28 : 24
Not Operating	4 : 47 ***
Bankrupt	57 : 0 ***
Market share of:	
Top 25%	26 : 28
Top 50%	13 : 17
Plant scale:	
Largest	57 : 7 ***
Average	49 : 15 ***
Technology:	
Best K	34 : 30
Best L	39 : 25
Average K	34 : 30
Average L	40 : 24 *

* = significant at 5% level; ** = 1% level; *** = 0.1% level

Appendix 9G: Market Share Results

WINNER T1	Time at which winner (firm at t=59 operating the largest capacity) first occupied first place
P1	Market share (%) of winner at T1
T2	Time at which winner first occupied either first or second place
P2	Market share (%) of winner at T2
SECOND T3	Time at which second firm (ranked second by capacity at t=59) first occupied either first or second place
P3	Market share (%) of second firm at T3
MAXPLANT PROPORTION	Percentage of time since T1 for which winner has operated the largest plant in the industry

RUN	------- WINNER		------		-SECOND-		MAXPLANT
	T1	P1	T2	P2	T3	P3	PROPORTION
16h1ivn.1	21	13.7	15	16.3	56	10.0	17.9
16h1ivn.2	59	13.8	59	13.8	43	11.9	0.0
16h1ivn.3	58	13.1	51	14.3	58	12.8	100.0
16h1ivn.4	53	16.3	36	13.7	55	11.5	28.6
16h1iin.1	58	9.9	55	9.2	59	10.7	0.0
16h1iin.2	59	16.8	48	15.2	55	14.0	100.0
16h1iin.3	53	13.8	52	12.8	59	9.7	57.1
16h1iin.4	59	12.1	59	12.1	55	13.4	0.0
16h4ivn.1	45	17.3	45	17.3	53	16.9	0.0
16h4ivn.2	33	27.4	33	27.4	59	20.3	11.1
16h4ivn.3	50	25.4	12	25.8	54	22.7	30.0
16h4ivn.4	50	20.1	41	21.7	59	18.5	0.0
16h4iin.1	59	19.4	59	19.4	10	26.5	0.0
16h4iin.2	55	31.1	44	22.6	56	23.4	0.0
16h4iin.3	49	20.6	44	24.6	58	14.4	45.5
16h4iin.4	57	25.0	56	20.5	59	17.9	0.0
1611ivn.1	59	14.1	59	14.1	25	13.5	0.0
1611ivn.2	59	17.1	32	15.8	39	15.0	0.0
1611ivn.3	20	18.8	19	13.6	57	11.1	17.5
1611ivn.4	27	18.7	24	16.0	57	13.0	9.1
1611iin.1	58	14.2	39	15.2	57	12.8	50.0
1611iin.2	15	19.2	10	18.4	56	12.9	11.1
1611iin.3	59	13.8	34	11.7	17	15.5	0.0
1611iin.4	36	17.8	14	14.8	56	10.4	25.0
1614ivn.1	47	34.9	43	17.6	10	36.6	0.0
1614ivn.2	44	22.5	25	27.2	47	22.1	87.5
1614ivn.3	35	28.8	20	27.5	10	37.0	32.0
1614ivn.4	6	41.3	1	6.3	52	17.9	53.7
1614iin.1	23	30.0	16	14.2	50	17.8	64.9
1614iin.2	56	31.9	49	23.1	15	16.6	25.0
1614iin.3	26	34.9	23	24.0	29	24.2	58.8
1614iin.4	21	30.9	15	13.6	43	19.7	53.8

RUN	------- WINNER ------				-SECOND-		MAXPLANT
	T1	P1	T2	P2	T3	P3	PROPORTION
16hliva.1	44	44.1	28	10.5	17	20.2	100.0
16hliva.2	6	33.3	3	16.7	49	11.0	92.6
16hliva.3	19	22.8	3	16.7	39	19.1	58.5
16hliva.4	44	24.0	44	24.0	53	15.1	81.3
16hliia.1	50	20.8	48	13.9	30	11.0	100.0
16hliia.2	44	20.7	23	11.4	56	19.9	100.0
16hliia.3	47	36.5	35	19.8	14	16.0	0.0
16hliia.4	42	13.6	36	10.8	55	16.2	94.4
16h4iva.1	24	22.5	24	22.5	53	6.0	94.4
16h4iva.2	31	30.3	30	29.2	56	18.2	100.0
16h4iva.3	49	39.5	3	29.4	29	20.1	63.6
16h4iva.4	25	41.4	12	27.7	31	26.3	100.0
16h4iia.1	59	32.8	58	24.3	48	24.6	0.0
16h4iia.2	54	24.9	54	24.9	56	22.1	83.3
16h4iia.3	24	38.7	14	20.5	56	17.0	75.0
16h4iia.4	18	45.5	11	22.7	56	3.6	83.3
16lliva.1	37	42.6	34	25.6	48	0.0	100.0
16lliva.2	21	39.0	15	13.9	53	10.3	100.0
16lliva.3	49	54.1	18	13.9	10	39.0	100.0
16lliva.4	4	21.9	3	19.4	53	11.8	83.9
16lliia.1	46	46.5	10	18.4	36	19.8	85.7
16lliia.2	39	42.2	30	13.6	55	20.8	100.0
16lliia.3	58	41.0	13	17.7	14	17.6	100.0
16lliia.4	11	23.8	10	20.6	39	23.5	83.7
16l4iva.1	9	34.6	1	6.3	58	4.1	84.3
16l4iva.2	19	56.0	5	17.4	55	0.0	61.0
16l4iva.3	6	38.1	5	18.5	58	10.0	87.0
16l4iva.4	8	38.0	5	11.4	31	9.4	92.3
16l4iia.1	59	22.6	54	25.8	59	22.4	100.0
16l4iia.2	18	35.9	16	30.5	55	12.1	100.0
16l4iia.3	18	26.8	18	26.8	55	23.1	100.0
16l4iia.4	34	24.7	34	24.7	56	0.0	76.9
16hlivb.1	33	31.5	28	19.0	18	16.4	100.0
16hlivb.2	54	28.5	53	22.6	35	12.8	66.7
16hlivb.3	4	15.4	4	15.4	34	13.0	50.0
16hlivb.4	54	38.7	51	23.1	27	15.6	100.0
16hliib.1	38	14.5	35	11.8	47	12.4	36.4
16hliib.2	14	12.1	14	12.1	56	15.5	76.1
16hliib.3	49	20.7	43	19.6	58	22.3	0.0
16hliib.4	54	33.7	43	17.4	28	12.9	0.0
16h4ivb.1	49	40.7	43	18.0	55	29.5	100.0
16h4ivb.2	58	20.5	58	20.5	53	22.2	0.0
16h4ivb.3	13	34.4	13	34.4	55	20.2	87.2
16h4ivb.4	54	31.3	29	24.4	58	26.3	0.0

RUN	WINNER T1	P1	T2	P2	SECOND T3	P3	MAXPLANT PROPORTION
16h4iib.1	19	21.2	19	21.2	43	6.4	100.0
16h4iib.2	32	18.1	17	22.9	56	16.2	100.0
16h4iib.3	25	26.8	10	28.9	55	9.4	77.1
16h4iib.4	55	14.4	55	14.4	48	12.2	0.0
16l1ivb.1	4	18.4	4	18.4	55	9.4	100.0
16l1ivb.2	8	28.8	7	19.1	51	7.7	98.1
16l1ivb.3	26	27.9	3	11.0	56	31.1	8.8
16l1ivb.4	31	18.3	31	18.3	49	8.3	100.0
16l1iib.1	35	26.1	34	20.7	39	26.5	76.0
16l1iib.2	46	35.5	38	12.4	14	18.3	42.9
16l1iib.3	35	27.6	35	27.6	48	0.0	100.0
16l1iib.4	48	39.3	24	11.1	17	10.6	100.0
16l4ivb.1	24	37.9	6	25.3	39	10.3	100.0
16l4ivb.2	3	28.6	3	28.6	56	10.6	96.5
16l4ivb.3	24	30.0	18	22.8	53	8.2	100.0
16l4ivb.4	16	25.6	15	19.9	58	0.0	77.3
16l4iib.1	10	23.7	1	6.3	41	0.0	68.0
16l4iib.2	35	15.9	35	15.9	54	15.4	76.0
16l4iib.3	19	15.8	19	15.8	26	8.9	95.1
16l4iib.4	32	24.8	30	15.4	56	19.2	32.1
16h1ivc.1	50	24.3	13	18.8	47	25.9	100.0
16h1ivc.2	20	17.6	15	13.2	47	16.7	35.0
16h1ivc.3	45	31.2	43	21.2	59	15.7	13.3
16h1ivc.4	16	16.6	14	12.3	49	21.4	97.7
16h1iic.1	43	18.5	41	17.3	53	15.6	5.9
16h1iic.2	47	13.3	46	13.2	58	13.1	0.0
16h1iic.3	27	14.7	17	11.8	55	12.2	72.7
16h1iic.4	17	15.4	14	13.5	59	13.6	60.5
16h4ivc.1	32	43.1	23	16.4	57	9.9	100.0
16h4ivc.2	56	30.0	53	26.0	55	32.4	0.0
16h4ivc.3	23	28.0	23	28.0	49	14.1	64.9
16h4ivc.4	42	33.3	40	21.2	31	37.8	0.0
16h4iic.1	49	29.1	44	23.2	52	22.5	36.4
16h4iic.2	49	23.9	32	19.8	58	17.8	0.0
16h4iic.3	3	26.2	3	26.2	57	19.7	100.0
16h4iic.4	48	31.2	3	26.2	21	22.1	100.0
16l1ivc.1	34	62.0	27	13.9	58	7.9	100.0
16l1ivc.2	14	17.1	14	17.1	49	0.0	100.0
16l1ivc.3	26	54.8	15	8.5	12	17.7	23.5
16l1ivc.4	25	30.7	19	12.1	46	0.0	94.3
16l1iic.1	21	10.9	21	10.9	41	12.7	92.3
16l1iic.2	15	11.9	15	11.9	53	13.5	28.9
16l1iic.3	58	17.8	56	15.8	41	10.1	0.0
16l1iic.4	50	14.0	50	14.0	55	12.1	60.0

RUN	WINNER T1	WINNER P1	WINNER T2	WINNER P2	-SECOND- T3	-SECOND- P3	MAXPLANT PROPORTION
1614ivc.1	3	24.0	3	24.0	27	0.0	98.2
1614ivc.2	54	42.9	21	22.4	14	28.6	66.7
1614ivc.3	32	39.5	14	32.3	51	0.0	100.0
1614ivc.4	25	49.8	14	18.3	59	20.7	5.7
1614iic.1	35	29.5	35	29.5	56	17.3	100.0
1614iic.2	55	28.0	45	17.2	55	21.6	0.0
1614iic.3	14	31.4	11	12.3	42	0.0	71.7
1614iic.4	32	32.3	24	15.1	27	23.0	100.0

Market Share Thresholds

F20 - the number of times a firm in the simulation achieves 20% market share, but fails to hold either first or second place for at least ten subsequent periods.
S20 - the number of times a firm in the simulation achieves 20% market share, and then holds either first or second place for at least the next ten periods.
F25, S25 etc - as F20, S20 but for 25% market share threshold. F30, .. etc defined similarly.

RUN	F20	S20	F25	S25	F30	S30	F35	S35	F40	S40	F45	S45	F50	S50
16hlivn.1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
16hlivn.2	1	0	0	0	1	0	0	0	0	0	0	0	0	0
16hlivn.3	1	2	0	0	0	0	0	0	0	0	0	0	0	0
16hlivn.4	0	1	0	0	0	0	0	0	0	0	0	0	0	0
16hliin.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16hliin.2	1	0	0	0	0	0	0	0	0	0	0	0	0	0
16hliin.3	2	0	0	0	0	0	0	0	0	0	0	0	0	0
16hliin.4	1	1	1	0	0	0	0	0	0	0	0	0	0	0
16h4ivn.1	2	2	1	0	0	2	0	0	0	1	0	1	0	1
16h4ivn.2	1	0	2	1	2	1	1	0	1	0	0	0	0	0
16h4ivn.3	0	1	3	1	1	2	0	0	0	1	0	1	0	1
16h4ivn.4	2	1	4	0	2	0	0	0	0	0	0	0	0	0
16h4iin.1	1	0	2	1	0	0	0	1	0	1	0	1	0	0
16h4iin.2	5	1	2	0	0	1	0	1	0	0	0	0	0	0
16h4iin.3	3	1	4	0	1	0	1	0	0	0	0	0	0	0
16h4iin.4	3	0	2	0	2	0	0	0	0	0	0	0	0	0
16llivn.1	3	1	1	0	0	0	0	0	0	0	0	0	0	0
16llivn.2	1	1	0	1	1	0	0	0	0	0	0	0	0	0
16llivn.3	2	1	1	1	0	1	0	1	0	0	0	0	0	0
16llivn.4	1	2	1	0	0	0	0	0	0	0	0	0	0	0
16lliin.1	2	1	0	1	0	0	0	0	0	0	0	0	0	0
16lliin.2	0	1	0	1	0	1	0	1	0	0	0	0	0	0
16lliin.3	2	1	0	1	0	1	0	1	0	0	0	0	0	0
16lliin.4	1	1	0	1	0	1	0	0	0	0	0	0	0	0

RUN	F20	S20	F25	S25	F30	S30	F35	S35	F40	S40	F45	S45	F50	S50
1614ivn.1	1	2	0	1	0	1	0	2	0	1	0	1	0	1
1614ivn.2	3	0	2	1	1	1	0	2	1	0	1	1	0	0
1614ivn.3	0	0	1	0	2	0	1	2	0	0	0	1	0	2
1614ivn.4	0	1	1	0	0	0	0	0	0	0	0	0	0	1
1614iin.1	2	1	2	0	2	1	1	1	0	1	0	1	0	1
1614iin.2	5	0	0	1	0	2	0	0	0	2	0	1	0	1
1614iin.3	1	1	2	1	0	2	2	1	0	2	1	1	0	1
1614iin.4	3	0	0	0	1	2	1	0	0	1	0	0	0	1
16hliva.1	1	1	0	1	1	1	0	1	0	2	0	2	0	2
16hliva.2	3	1	1	0	0	1	0	1	0	0	0	1	0	1
16hliva.3	2	0	0	2	0	2	0	1	0	1	0	0	0	1
16hliva.4	3	1	0	3	0	0	0	0	0	0	0	0	0	0
16hliia.1	0	2	0	1	0	0	0	0	0	0	0	0	0	0
16hliia.2	1	2	0	2	0	0	0	0	0	0	0	0	0	0
16hliia.3	2	2	0	2	0	2	0	1	0	1	0	0	0	0
16hliia.4	1	1	1	0	0	0	0	0	0	0	0	0	0	0
16h4iva.1	2	1	1	0	0	1	1	1	0	0	0	1	0	1
16h4iva.2	0	1	0	2	1	2	2	1	0	1	0	2	0	1
16h4iva.3	2	1	1	1	0	2	0	2	0	3	0	0	0	1
16h4iva.4	1	1	2	2	0	1	0	2	0	1	0	1	0	1
16h4iia.1	3	0	2	0	1	2	1	1	0	1	0	1	0	0
16h4iia.2	1	1	2	0	0	0	0	0	0	1	0	0	0	0
16h4iia.3	4	1	4	0	1	0	0	1	0	0	0	1	0	0
16h4iia.4	0	1	1	0	0	1	0	1	0	0	0	2	0	2
16lliva.1	1	0	1	2	0	0	0	0	0	1	0	2	0	2
16lliva.2	0	1	0	0	0	1	0	2	0	1	0	0	0	2
16lliva.3	0	1	1	1	0	0	0	2	0	1	0	2	0	2
16lliva.4	0	1	1	0	0	0	0	1	0	1	0	0	0	1
16lliia.1	2	1	0	1	0	2	0	2	0	1	0	1	0	2
16lliia.2	0	2	0	2	0	1	0	1	0	1	0	0	0	1
16lliia.3	2	2	0	2	0	2	0	1	0	1	0	1	0	1
16lliia.4	2	2	0	0	0	1	0	2	0	1	0	1	0	1
1614iva.1	0	0	1	0	0	1	0	0	0	0	0	0	0	1
1614iva.2	0	1	0	1	0	1	0	1	0	0	0	1	0	2
1614iva.3	0	1	1	0	0	0	0	0	0	0	0	0	0	1
1614iva.4	0	0	1	1	0	0	0	2	0	0	0	0	0	1
1614iia.1	3	2	0	3	0	0	0	0	0	1	0	0	0	0
1614iia.2	0	0	1	0	1	1	0	1	0	0	0	1	1	1
1614iia.3	3	1	2	1	1	0	0	1	0	0	0	1	0	1
1614iia.4	4	0	2	1	1	1	0	3	0	1	0	1	1	1
16hlivb.1	1	2	0	0	0	2	0	0	0	1	0	1	0	1
16hlivb.2	0	2	1	1	0	0	0	0	0	0	0	0	0	0
16hlivb.3	0	1	0	1	0	0	0	1	0	0	0	0	0	1
16hlivb.4	1	0	0	0	0	1	0	0	0	1	0	0	0	0

RUN	F20	S20	F25	S25	F30	S30	F35	S35	F40	S40	F45	S45	F50	S50
16h1iib.1	0	1	0	1	0	1	0	0	0	0	0	0	0	0
16h1iib.2	0	1	0	1	0	0	0	0	0	0	0	0	0	0
16h1iib.3	0	3	0	1	0	0	0	0	0	0	0	0	0	0
16h1iib.4	1	3	0	2	0	0	0	0	0	0	0	0	0	0
16h4ivb.1	2	1	0	1	0	1	1	0	0	2	0	1	0	1
16h4ivb.2	1	2	0	1	1	0	0	1	0	0	0	0	0	0
16h4ivb.3	1	0	1	0	1	1	0	1	0	1	0	1	0	1
16h4ivb.4	3	0	1	0	1	1	1	1	0	1	0	0	0	0
16h4iib.1	4	0	1	0	0	1	0	0	0	1	0	1	0	1
16h4iib.2	0	1	2	1	1	0	0	0	0	0	0	0	0	0
16h4iib.3	3	1	2	1	0	0	0	1	0	1	0	0	0	0
16h4iib.4	0	3	0	2	1	0	0	0	0	0	0	0	0	0
16l1ivb.1	0	1	0	0	0	1	0	0	0	1	0	0	0	1
16l1ivb.2	1	0	0	0	0	1	0	1	0	1	0	0	0	1
16l1ivb.3	2	1	2	1	1	2	0	2	0	1	1	0	0	0
16l1ivb.4	0	3	1	1	0	0	0	1	0	1	0	0	0	1
16l1iib.1	1	2	0	2	0	1	0	2	0	0	0	1	0	1
16l1iib.2	0	1	0	2	0	1	0	2	0	1	0	1	0	1
16l1iib.3	1	0	0	2	0	1	0	1	0	0	0	1	0	1
16l1iib.4	0	2	0	2	0	2	0	2	0	2	0	0	0	0
16l4ivb.1	1	2	1	0	1	1	2	1	1	1	0	1	0	1
16l4ivb.2	0	0	0	1	0	1	0	0	0	0	0	0	0	1
16l4ivb.3	3	0	1	0	1	1	0	0	0	1	0	0	0	1
16l4ivb.4	2	0	1	3	1	2	0	1	0	1	0	1	0	1
16l4iib.1	1	1	0	0	0	1	0	1	0	0	0	1	0	1
16l4iib.2	2	0	0	1	1	0	0	1	0	1	0	1	0	1
16l4iib.3	2	1	0	1	0	2	0	2	0	1	0	2	0	1
16l4iib.4	2	1	1	1	0	1	0	1	0	0	0	0	0	0
16h1ivc.1	0	2	1	1	1	0	0	0	0	0	0	0	0	0
16h1ivc.2	0	1	0	1	0	1	0	1	0	1	0	1	0	0
16h1ivc.3	1	2	0	1	0	2	0	2	0	0	0	0	0	0
16h1ivc.4	0	3	0	1	0	1	0	0	0	1	0	1	0	1
16h1iic.1	1	1	0	2	0	0	0	0	0	0	0	0	0	0
16h1iic.2	0	1	0	0	0	0	0	0	0	0	0	0	0	0
16h1iic.3	0	1	0	1	0	1	0	0	0	0	0	0	0	0
16h1iic.4	0	1	0	0	0	0	0	0	0	0	0	0	0	0
16h4ivc.1	3	0	1	2	0	1	0	1	0	2	0	1	0	1
16h4ivc.2	2	1	0	3	0	1	0	0	0	0	0	0	0	0
16h4ivc.3	1	1	1	2	0	1	0	1	0	1	0	0	0	1
16h4ivc.4	2	2	1	3	0	1	0	2	0	1	0	1	0	0
16h4iic.1	3	1	0	2	0	2	0	0	0	0	0	0	0	0
16h4iic.2	3	1	3	2	3	1	1	0	0	0	0	0	0	0
16h4iic.3	1	0	0	1	0	1	0	0	0	0	0	1	0	0
16h4iic.4	0	1	0	1	0	2	0	1	0	0	0	1	0	0

RUN	F20	S20	F25	S25	F30	S30	F35	S35	F40	S40	F45	S45	F50	S50
1611ivc.1	1	2	1	4	0	0	0	2	0	1	0	1	0	2
1611ivc.2	0	1	0	2	0	1	0	1	0	1	0	1	0	1
1611ivc.3	0	1	0	0	0	2	0	1	0	1	0	2	0	2
1611ivc.4	0	1	0	2	0	2	0	1	0	1	0	0	0	1
1611iic.1	0	2	0	0	0	1	0	1	0	0	0	0	0	1
1611iic.2	1	1	0	1	0	1	0	1	0	0	0	0	0	0
1611iic.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1611iic.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1614ivc.1	1	0	1	1	0	0	0	1	0	1	0	0	0	1
1614ivc.2	2	0	0	1	0	1	1	1	1	1	0	1	0	1
1614ivc.3	1	0	2	0	0	2	0	1	0	1	0	0	0	1
1614ivc.4	3	0	1	0	0	2	0	1	0	2	0	2	0	1
1614iic.1	2	1	2	1	0	1	0	2	0	1	0	0	0	1
1614iic.2	0	3	1	2	1	2	0	1	0	1	0	0	0	0
1614iic.3	1	1	0	1	0	1	0	1	0	1	0	1	0	1
1614iic.4	1	2	0	1	0	3	0	1	0	1	0	1	0	1

Appendix 9H: Market Share Results Analysis

This Appendix gives the detailed analysis of the market share results. The output performance measures used are as follows:

Winner 1st since	The time (simulation period) at which the firm with the largest market share at t=59 first occupied the leading position, and then kept it
with mkt share %	The percentage market share the winner had at that time it first emerged
Winner in top 2 since	As above, but the period at which the winner first occupied either first or second place
with mkt share %	Market share on occupying first or second place
Winner max. plant %	The proportion of the time that the winner has been in first place for which it has operated a bigger plant than all its competitors
20% threshold - Fail	Counts the number of times firms gain 20% market share, but do not hold either first or second place for at least the ten subsequent periods
20% threshold - Succeed	Counts the number of times firms gain 20% market share, and go on to hold either first or second place for the next ten periods or more.

NB "threshold" statistics are actual total frequencies, not comparisons.

The motivation for these measures is to give an idea of the persistence of market share leadership. A "snapshot" at t=59 shows how long the successful firms at that period have been in leading positions. The threshold measures give incidences of success and failure in market dominance for firms which have already acheived a particular market share level.

Measurement of threshold results is only begun at t=10 within the simulations. In the early stages of the simulations, small capacity additions can lead to relatively big market share swings, so market share thresholds are only assessed after the first ten simulated periods have elapsed. Only 16-firm scenarios are used, as explained in Chapter 9, section 3.

The tables below report the results in three ways. Firstly, under the columns marked "counts", they count the number of times the particular output measure was larger at t=59 for runs with the relevant experimental variable. Secondly, under "averages", they report the average value of the output measure. So, for example, the first table below, where technical change is the experimental influence for comparisons, reports that 25 times out of the 32 the winning firm emerged later for runs with no technical change allowed. The average time at which winners in the no technical change runs emerged was t = 44, whilst for runs with technical change the average was at t = 31.8.

The third way results are reported is in the "thresholds" section. The table below shows, for example, that over the 32 runs with no technical change, there were 50 occasions when a firm reached a 20% market share and then did not stay in the top two for ten periods. There were 25 occasions when a firm reached a 20% threshold and then did succeed in holding one of the two leading positions. For runs with technical change allowed, the proportions were 43 failures and 32 successes at the 20% threshold.

COMPARISONS ON TECHNICAL CHANGE (TC) VS. NO TECHNICAL CHANGE (NTC)
(Demand series A only)

	Counts NTC : TC		Averages NTC	TC
Winner 1st since	25 : 6	***	44.0	31.8
with mkt share %	6 :26	***	21.4	33.7
Winner in top 2 since	25 : 7	**	35.4	21.8
with mkt share %	9 :23	*	17.5	19.7
Winner max. plant %	3 :27	***	27.5	83.8

* = significant at 5% level; ** = 1% level; *** = 0.1% level (see Appendix 9D for details)

Thresholds (totalled over all runs):

	NTC		TC	
	Fail	Succeed	Fail	Succeed
20% threshold	50	25	43	32
25% threshold	32	13	26	31
30% threshold	16	19	7	26
35% threshold	7	13	4	21
40% threshold	2	10	0	21
45% threshold	2	9	0	22
50% threshold	0	10	2	30

NOTE: It may seem surprising that the TC results show 30 successes at the 50% threshold but only 22 at the 45%'. It is, however, correct, and is the product of two factors:

(i) adding a large plant can increase market share significantly, in some cases by as much as 20%. Thus a firm can "skip" thresholds.

(ii) as noted above, measurement is only started at t=10. A firm can thus start at a high threshold, without having been counted at lower thresholds.

SIGNIFICANT DIFFERENCES BETWEEN THRESHOLDS FOR NTC AND TC RUNS

The proportions of firms reaching a given market share threshold and then either succeeding (holding a top-two position for ten periods or more) or failing appear to differ between runs with and without technical change allowed. This observation can be checked by applying a Chi-squared test to the relative proportions for each of the thresholds separately.

The hypothesis that "there is no difference between the chances of success and failure at the X% threshold for firms in simulations with and without technical change allowed" was tested, where X was equal to 20%, 25%, 30%, and 35% and above. With one degree of freedom, the Chi-squared statistic was acceptable for X = 20% only. For X at 25% and at 35% and above the hypothesis was rejected at the 1% level; at X of 30% it was rejected at the 5% level.

It was therefore concluded that the chances of failure and success at different thresholds is significantly different for simulations with and without technical change.

COMPARISONS ON WORLDVIEW II VS. IV
(All demand series)

	Counts II : IV		Averages II	Averages IV
Winner 1st since	32 :15	*	36.0	28.1
with mkt share %	11 :37	***	25.3	33.0
Winner in top 2 since	30 :17		28.6	19.8
with mkt share %	20 :27		18.3	19.8
Winner max. plant %	14 :27	*	64.4	74.6

* = significant at 5% level; ** = 1% level; *** = 0.1% level (see Appendix 9D for details)

Thresholds (totalled over all runs):

	Worldview II Fail	Worldview II Succeed	Worldview IV Fail	Worldview IV Succeed
20% threshold	58	58	50	44
25% threshold	27	50	29	50
30% threshold	12	40	10	46
35% threshold	2	36	8	43
40% threshold	0	20	2	40
45% threshold	0	22	1	28
50% threshold	2	21	0	44

COMPARISONS ON INITIAL MAXIMUM PLANT SCALE 100 VS. 400
(All demand series)

	Counts 100 : 400		Averages 100	400
Winner 1st since	24 :22		33.4	30.7
with mkt share %	18 :30		27.4	30.9
Winner in top 2 since	25 :22		25.4	23.0
with mkt share %	9 :39	***	16.1	22.0
Winner max. plant %	21 :20		69.1	69.9

* = significant at 5% level; ** = 1% level; *** = 0.1% level (see Appendix 9D for details)

Thresholds (totalled over all runs):

	Plant scale 100 Fail	Succeed	Plant scale 400 Fail	Succeed
20% threshold	32	63	76	39
25% threshold	11	52	45	48
30% threshold	3	38	19	48
35% threshold	0	37	10	42
40% threshold	0	27	2	33
45% threshold	1	20	0	30
50% threshold	0	32	2	33

COMPARISONS ON CAPITAL INTENSITY LOW VS. HIGH
(All demand series)

	Counts Low : High		Averages Low	High
Winner 1st since	14 :33	**	27.6	36.5
with mkt share %	29 :19		31.4	26.9
Winner in top 2 since	18 :30		20.0	28.4
with mkt share %	20 :28		18.1	20.0
Winner max. plant %	25 :15		78.5	60.5

* = significant at 5% level; ** = 1% level; *** = 0.1% level (see Appendix 9D for details)

Thresholds (totalled over all runs):

	Low cap. intensity Fail	Succeed	High cap. intensity Fail	Succeed
20% threshold	48	45	60	57
25% threshold	26	48	30	52
30% threshold	9	48	13	38
35% threshold	3	53	7	26
40% threshold	2	35	0	25
45% threshold	1	29	0	21
50% threshold	2	47	0	18

COMPARISONS ON DEMAND SERIES A VS. B

	Counts A : B		Averages A	B
Winner 1st since	15 :17		31.8	31.3
with mkt share %	25 : 7	**	33.7	25.8
Winner in top 2 since	11 :20		21.8	25.6
with mkt share %	19 :13		19.7	19.2
Winner max. plant %	17 :11		83.8	67.6

* = significant at 5% level; ** = 1% level; *** = 0.1% level (see Appendix 9D for details)

Thresholds (totalled over all runs):

	Demand Series A		Demand Series B	
	Fail	Succeed	Fail	Succeed
20% threshold	43	32	35	36
25% threshold	26	31	15	30
30% threshold	7	26	10	26
35% threshold	4	32	4	23
40% threshold	0	21	1	20
45% threshold	0	22	1	13
50% threshold	2	30	0	18

COMPARISONS ON DEMAND SERIES A VS. C

	Counts A : C	Averages A	C
Winner 1st since	17 :14	31.8	33.1
with mkt share %	21 :11	33.7	27.9
Winner in top 2 since	17 :15	21.8	25.3
with mkt share %	19 :13	19.7	18.2
Winner max. plant %	15 :13	83.8	57.1

* = significant at 5% level; ** = 1% level; *** = 0.1% level (see Appendix 9D for details)

Thresholds (totalled over all runs):

	Demand Series A		Demand Series C	
	Fail	Succeed	Fail	Succeed
20% threshold	43	32	30	34
25% threshold	26	31	15	39
30% threshold	7	26	5	34
35% threshold	4	32	2	24
40% threshold	0	21	1	19
45% threshold	0	22	0	15
50% threshold	2	30	0	17

COMPARISONS ON DEMAND SERIES B VS. C

	Counts B : C	Averages B	Averages C
Winner 1st since	14 :16	31.1	33.1
with mkt share %	13 :19	25.8	27.9
Winner in top 2 since	17 :15	25.6	25.3
with mkt share %	22 :10	19.2	18.2
Winner max. plant %	17 :19	67.6	57.1

* = significant at 5% level; ** = 1% level; *** = 0.1% level (see Appendix 9D for details)

Thresholds (totalled over all runs):

	Demand Series B Fail	Demand Series B Succeed	Demand Series C Fail	Demand Series C Succeed
20% threshold	35	36	30	34
25% threshold	15	30	15	39
30% threshold	10	26	5	34
35% threshold	4	23	2	24
40% threshold	1	20	1	19
45% threshold	1	13	0	15
50% threshold	0	18	0	17

Appendix 9I: Results of Competitions Between Worldview II and IV

The 16-firm runs using demand series A were repeated. 8 firms were given worldview II and 8 were given worldview IV. The results obtained for these 16 runs are listed below. They show the numbers of firms left operating, bankrupt, and "not operating" (i.e. running no plants, but not bankrupt) at the end of each of the runs for each worldview. They also show the percentage of the total capital of all firms held by each worldview.

RUN	WORLDVIEW II				WORLDVIEW IV			
	No. of firms				No. of firms			
	Operating	Not Operating	Bankrupt	% of capital	Operating	Not Operating	Bankrupt	% of capital
16H1A.1	0	6	2	38%	6	0	2	62%
16H1A.2	0	5	3	28%	4	2	2	72%
16H1A.3	0	6	2	38%	2	1	5	62%
16H1A.4	0	3	5	22%	2	2	4	78%
16H4A.1	0	6	2	31%	2	0	6	69%
16H4A.2	0	4	4	26%	1	0	7	74%
16H4A.3	0	5	3	40%	2	1	5	60%
16H4A.4	1	3	4	27%	3	1	4	73%
16L1A.1	0	6	2	28%	6	2	0	72%
16L1A.2	0	7	1	20%	5	1	2	80%
16L1A.3	0	5	3	29%	4	2	2	71%
16L1A.4	0	7	1	31%	1	5	2	69%
16L4A.1	0	7	1	36%	3	2	3	64%
16L4A.2	0	6	2	16%	2	3	3	84%
16L4A.3	0	8	0	25%	4	3	1	75%
16L4A.4	0	8	0	25%	2	2	4	75%

Appendix 9J: Profitability Results

WINNER'S ABSOLUTE - Total profit of firm with largest profit

" PERCENT - same expressed as percentage of total for all firms

TOP QUARTILE - both measures as for WINNER, but for best 25% of firms

INDUSTRY TOTAL - Sum of all firms' profits

"Profit" here means total accumulated Capital - Debt at t=59. (Note Debt can be negative i.e. it can be a positive cash balance. See Chapter 7.)

RUN	WINNER'S		TOP QUARTILE		INDUSTRY
	ABSOLUTE	PERCENT	ABSOLUTE	PERCENT	TOTAL
4hlivn.1	87260	30.90	87260	30.90	282146
4hlivn.2	86244	31.20	86244	31.20	276465
4hlivn.3	89679	32.20	89679	32.20	278700
4hlivn.4	80783	29.50	80783	29.50	273527
4hliin.1	102404	26.20	102404	26.20	391534
4hliin.2	111510	27.40	111510	27.40	407674
4hliin.3	112356	27.90	112356	27.90	402773
4hliin.4	102410	25.90	102410	25.90	394908
4h4ivn.1	92590	58.80	92590	58.80	157450
4h4ivn.2	102676	50.80	102676	50.80	202310
4h4ivn.3	85046	48.00	85046	48.00	177129
4h4ivn.4	71796	40.90	71796	40.90	175460
4h4iin.1	123507	41.10	123507	41.10	300244
4h4iin.2	157232	53.50	157232	53.50	293705
4h4iin.3	122376	41.80	122376	41.80	292781
4h4iin.4	122395	41.60	122395	41.60	294364
411ivn.1	55665	27.10	55665	27.10	205099
411ivn.2	64307	31.10	64307	31.10	207052
411ivn.3	61389	28.40	61389	28.40	216418
411ivn.4	64315	30.40	64315	30.40	211574
411iin.1	82341	26.50	82341	26.50	311062
411iin.2	96295	30.60	96295	30.60	314288
411iin.3	90715	28.90	90715	28.90	313436
411iin.4	91739	29.40	91739	29.40	311653
414ivn.1	119168	95.40	119168	95.40	124918
414ivn.2	45779	34.10	45779	34.10	134139
414ivn.3	60632	43.10	60632	43.10	140761
414ivn.4	69648	49.20	69648	49.20	141515
414iin.1	67729	31.30	67729	31.30	216105
414iin.2	71334	32.30	71334	32.30	220715
414iin.3	96162	43.50	96162	43.50	220932
414iin.4	72139	36.20	72139	36.20	199229

RUN	WINNER'S ABSOLUTE	WINNER'S PERCENT	TOP QUARTILE ABSOLUTE	TOP QUARTILE PERCENT	INDUSTRY TOTAL
16hlivn.1	47876	12.70	150486	39.90	377599
16hlivn.2	49698	14.30	171736	49.50	347148
16hlivn.3	46638	12.60	166487	44.80	371253
16hlivn.4	42061	11.00	161765	42.50	381045
16hliin.1	50239	9.00	186724	33.30	560892
16hliin.2	64408	11.40	214498	37.80	567409
16hliin.3	59258	10.50	202540	35.70	566671
16hliin.4	69158	12.70	216714	39.90	542492
16h4ivn.1	54774	19.60	156940	56.10	279570
16h4ivn.2	81014	28.00	196192	67.80	289581
16h4ivn.3	69890	24.10	168330	58.00	290077
16h4ivn.4	46986	16.30	171930	59.70	288073
16h4iin.1	108882	22.20	222608	45.50	489504
16h4iin.2	87659	19.70	244579	55.00	444823
16h4iin.3	64322	14.90	251111	58.20	431423
16h4iin.4	78892	18.60	271926	64.00	424942
16llivn.1	32810	9.80	121360	36.30	334202
16llivn.2	33102	10.50	123729	39.30	315004
16llivn.3	46974	15.40	130291	42.60	305548
16llivn.4	45998	14.80	130856	42.10	310726
16lliin.1	54538	11.20	194070	39.80	487965
16lliin.2	78723	15.90	206904	41.80	494658
16lliin.3	66447	13.80	184528	38.30	482316
16lliin.4	64028	13.10	195682	40.20	487187
16l4ivn.1	60859	29.00	136479	65.10	209631
16l4ivn.2	45504	21.80	141069	67.60	208545
16l4ivn.3	46625	24.10	141491	73.10	193606
16l4ivn.4	62405	26.10	141284	59.00	239520
16l4iin.1	98150	28.00	223797	63.90	350038
16l4iin.2	78457	21.50	222103	61.00	364310
16l4iin.3	87164	23.50	216683	58.50	370131
16l4iin.4	82084	23.30	205273	58.30	352197
4hliva.1	119563	70.70	119563	70.70	169042
4hliva.2	98149	74.20	98149	74.20	132298
4hliva.3	186178	92.60	186178	92.60	200976
4hliva.4	125684	73.70	125684	73.70	170571
4hliia.1	134636	50.90	134636	50.90	264428
4hliia.2	100246	31.60	100246	31.60	317329
4hliia.3	171275	60.10	171275	60.10	284979
4hliia.4	127525	46.10	127525	46.10	276570
4h4iva.1	114829	106.00	114829	106.00	108368
4h4iva.2	65183	51.80	65183	51.80	125781
4h4iva.3	86202	95.80	86202	95.80	89970
4h4iva.4	116253	91.00	116253	91.00	127691

RUN	WINNER'S ABSOLUTE	WINNER'S PERCENT	TOP QUARTILE ABSOLUTE	TOP QUARTILE PERCENT	INDUSTRY TOTAL
4h4iia.1	141911	74.00	141911	74.00	191727
4h4iia.2	140059	59.80	140059	59.80	234138
4h4iia.3	85210	38.40	85210	38.40	222011
4h4iia.4	109035	50.60	109035	50.60	215331
411iva.1	107033	71.70	107033	71.70	149320
411iva.2	76370	70.80	76370	70.80	107817
411iva.3	58355	99.90	58355	99.90	58385
411iva.4	58319	69.90	58319	69.90	83470
411iia.1	126905	69.60	126905	69.60	182371
411iia.2	129205	81.50	129205	81.50	158545
411iia.3	92604	58.80	92604	58.80	157537
411iia.4	134577	53.90	134577	53.90	249613
414iva.1	37213	71.60	37213	71.60	51979
414iva.2	77738	100.00	77738	100.00	77768
414iva.3	96184	83.60	96184	83.60	115058
414iva.4	83783	100.00	83783	100.00	83813
414iia.1	76965	50.90	76965	50.90	151210
414iia.2	109459	66.60	109459	66.60	164240
414iia.3	114588	69.60	114588	69.60	164548
414iia.4	79642	50.90	79642	50.90	156515
16h1iva.1	70039	30.00	174678	74.70	233774
16h1iva.2	103617	69.60	145401	97.70	148852
16h1iva.3	97936	43.60	171526	76.40	224451
16h1iva.4	59397	26.70	150254	67.60	222327
16h1iia.1	78411	14.70	233841	43.90	532700
16h1iia.2	78000	15.80	245651	49.80	493399
16h1iia.3	98738	23.10	226322	53.00	427171
16h1iia.4	66340	13.40	216078	43.60	495854
16h4iva.1	88019	59.40	135482	91.40	148165
16h4iva.2	78161	45.80	152852	89.60	170612
16h4iva.3	75681	36.30	166466	79.90	208453
16h4iva.4	106432	46.10	193859	83.90	230991
16h4iia.1	85051	20.70	257446	62.50	411807
16h4iia.2	68253	17.10	219032	54.80	399908
16h4iia.3	99778	26.80	219684	59.10	371778
16h4iia.4	113839	43.00	177786	67.10	264889
1611iva.1	34610	34.60	78257	78.20	100064
1611iva.2	75846	39.30	134861	69.90	193059
1611iva.3	43756	32.60	103668	77.20	134290
1611iva.4	77464	41.50	126833	67.90	186657
1611iia.1	66657	19.70	181335	53.50	338838
1611iia.2	95555	25.60	197019	52.90	372759
1611iia.3	95022	24.50	226352	58.40	387619
1611iia.4	113611	35.30	213806	66.40	321957

RUN	WINNER'S ABSOLUTE	WINNER'S PERCENT	TOP QUARTILE ABSOLUTE	TOP QUARTILE PERCENT	INDUSTRY TOTAL
1614iva.1	97379	71.00	131431	95.80	137177
1614iva.2	41398	46.30	70837	79.20	89489
1614iva.3	80184	43.30	135589	73.30	185060
1614iva.4	75269	42.90	141775	80.80	175367
1614iia.1	65166	17.40	191016	51.10	374073
1614iia.2	111526	40.80	174090	63.60	273628
1614iia.3	100501	32.20	182253	58.40	312001
1614iia.4	62237	24.50	157336	61.90	254367
4hlivb.1	152205	58.50	152205	58.50	260309
4hlivb.2	107284	57.40	107284	57.40	187068
4hlivb.3	234516	103.80	234516	103.80	225992
4hlivb.4	157230	59.80	157230	59.80	263102
4hliib.1	178709	32.80	178709	32.80	544354
4hliib.2	343118	90.70	343118	90.70	378182
4hliib.3	187091	52.90	187091	52.90	353846
4hliib.4	314409	63.00	314409	63.00	498938
4h4ivb.1	208318	100.00	208318	100.00	208348
4h4ivb.2	172880	100.00	172880	100.00	172910
4h4ivb.3	112100	45.00	112100	45.00	249021
4h4ivb.4	237731	100.00	237731	100.00	237761
4h4iib.1	190967	68.80	190967	68.80	277561
4h4iib.2	197387	57.00	197387	57.00	346158
4h4iib.3	204616	71.40	204616	71.40	286690
4h4iib.4	212752	62.20	212752	62.20	342315
411ivb.1	112493	100.00	112493	100.00	112523
411ivb.2	144718	96.10	144718	96.10	150623
411ivb.3	367820	78.50	367820	78.50	468683
411ivb.4	74454	40.10	74454	40.10	185666
411iib.1	180062	60.60	180062	60.60	297197
411iib.2	123979	36.50	123979	36.50	339626
411iib.3	114498	40.40	114498	40.40	283557
411iib.4	212895	91.00	212895	91.00	233992
414ivb.1	193526	100.00	193526	100.00	193556
414ivb.2	213462	100.00	213462	100.00	213492
414ivb.3	88385	60.60	88385	60.60	145924
414ivb.4	54494	66.40	54494	66.40	82050
414iib.1	172699	56.20	172699	56.20	307530
414iib.2	175119	70.80	175119	70.80	247240
414iib.3	221010	84.10	221010	84.10	262725
414iib.4	106874	48.30	106874	48.30	221164
16hlivb.1	133758	35.50	282424	75.00	376814
16hlivb.2	95416	21.30	284599	63.50	448069
16hlivb.3	208415	59.00	271988	76.90	353477
16hlivb.4	108714	30.10	288532	79.90	361187

RUN	WINNER'S ABSOLUTE	WINNER'S PERCENT	TOP QUARTILE ABSOLUTE	TOP QUARTILE PERCENT	INDUSTRY TOTAL
16h1iib.1	163220	21.50	364471	48.00	759223
16h1iib.2	165132	21.80	365839	48.20	759060
16h1iib.3	125837	19.20	387624	59.30	653957
16h1iib.4	127412	17.30	380169	51.50	738171
16h4ivb.1	90569	27.80	264118	81.10	325644
16h4ivb.2	99134	23.80	261689	62.90	415760
16h4ivb.3	130027	42.30	269430	87.70	307292
16h4ivb.4	97323	28.30	231551	67.30	343920
16h4iib.1	293544	53.40	402176	73.20	549415
16h4iib.2	127761	19.20	303283	45.50	667061
16h4iib.3	174830	30.60	350538	61.40	570862
16h4iib.4	106059	15.50	341237	50.00	682904
1611ivb.1	143229	52.50	212025	77.80	272669
1611ivb.2	141389	60.90	187036	80.50	232231
1611ivb.3	82851	28.30	207411	70.90	292415
1611ivb.4	134580	47.70	203774	72.30	281911
1611iib.1	119689	28.50	257809	61.40	419565
1611iib.2	149082	30.70	318477	65.60	485795
1611iib.3	106712	26.70	223530	55.90	400069
1611iib.4	151881	28.00	328060	60.60	541547
1614ivb.1	100475	42.80	199537	85.10	234593
1614ivb.2	107640	63.50	143878	84.90	169464
1614ivb.3	155067	59.60	228056	87.70	259996
1614ivb.4	134059	60.70	201799	91.40	220786
1614iib.1	141930	39.30	218251	60.40	361195
1614iib.2	130387	24.10	253896	47.00	540660
1614iib.3	194529	42.80	309517	68.10	454410
1614iib.4	102289	18.00	314502	55.30	569140
4h1ivc.1	131156	58.20	131156	58.20	225369
4h1ivc.2	112693	48.20	112693	48.20	233666
4h1ivc.3	94684	36.80	94684	36.80	257283
4h1ivc.4	110288	52.80	110288	52.80	208850
4h1iic.1	178962	55.60	178962	55.60	321938
4h1iic.2	185405	45.10	185405	45.10	411240
4h1iic.3	186382	47.90	186382	47.90	388922
4h1iic.4	218046	67.40	218046	67.40	323631
4h4ivc.1	81207	43.00	81207	43.00	188656
4h4ivc.2	107617	50.90	107617	50.90	211250
4h4ivc.3	101311	65.70	101311	65.70	154184
4h4ivc.4	121654	64.00	121654	64.00	190223
4h4iic.1	113005	38.70	113005	38.70	291721
4h4iic.2	151947	50.40	151947	50.40	301454
4h4iic.3	116132	37.00	116132	37.00	314064
4h4iic.4	198174	64.90	198174	64.90	305565

RUN	WINNER'S ABSOLUTE	WINNER'S PERCENT	TOP QUARTILE ABSOLUTE	TOP QUARTILE PERCENT	INDUSTRY TOTAL
411ivc.1	139720	83.80	139720	83.80	166745
411ivc.2	82074	55.20	82074	55.20	148814
411ivc.3	120559	72.90	120559	72.90	165443
411ivc.4	40609	32.10	40609	32.10	126602
411iic.1	176734	61.30	176734	61.30	288498
411iic.2	192945	49.30	192945	49.30	391058
411iic.3	185669	66.50	185669	66.50	279275
411iic.4	161509	73.70	161509	73.70	219078
414ivc.1	99140	64.20	99140	64.20	154503
414ivc.2	67970	51.30	67970	51.30	132552
414ivc.3	110854	80.90	110854	80.90	137110
414ivc.4	99241	68.20	99241	68.20	145466
414iic.1	126399	66.10	126399	66.10	191359
414iic.2	152643	73.80	152643	73.80	206740
414iic.3	125748	47.60	125748	47.60	264337
414iic.4	118797	63.40	118797	63.40	187472
16h1ivc.1	71536	15.20	210142	44.60	470836
16h1ivc.2	116926	25.10	231380	49.60	466216
16h1ivc.3	86024	17.70	236324	48.80	484710
16h1ivc.4	118135	24.50	250038	51.80	482311
16h1iic.1	96805	14.70	291051	44.10	659522
16h1iic.2	83492	12.10	254489	36.80	691542
16h1iic.3	96372	14.60	247113	37.50	659476
16h1iic.4	90756	13.20	278936	40.50	688313
16h4ivc.1	92771	26.60	206014	59.00	349261
16h4ivc.2	66948	15.40	201555	46.30	435047
16h4ivc.3	112955	28.40	247907	62.20	398348
16h4ivc.4	85288	23.30	201292	54.90	366828
16h4iic.1	85694	15.10	283619	49.90	568872
16h4iic.2	76351	13.50	273538	48.50	563887
16h4iic.3	156381	26.10	306956	51.20	599078
16h4iic.4	151784	26.70	326820	57.40	569460
1611ivc.1	90634	24.70	162309	44.30	366230
1611ivc.2	76186	23.10	132758	40.20	330216
1611ivc.3	75912	20.50	179516	48.40	370740
1611ivc.4	31461	12.10	90083	34.70	259961
1611iic.1	137076	26.90	237989	46.60	510226
1611iic.2	112585	19.60	260782	45.40	573817
1611iic.3	54172	9.20	197064	33.50	588305
1611iic.4	56527	9.70	200052	34.30	583458
1614ivc.1	111189	33.50	163434	49.30	331840
1614ivc.2	54599	16.10	166434	49.10	339254
1614ivc.3	73687	22.90	174979	54.40	321944
1614ivc.4	84113	21.80	190517	49.30	386108

RUN	WINNER'S		TOP QUARTILE		INDUSTRY
	ABSOLUTE	PERCENT	ABSOLUTE	PERCENT	TOTAL
1614iic.1	76009	15.40	257301	52.20	492864
1614iic.2	76619	15.40	222408	44.60	498885
1614iic.3	133320	31.60	228378	54.10	422469
1614iic.4	86336	18.20	245696	51.70	474852

Appendix 9K: Profitability Paired Comparisons

The tables report the frequency of the particular comparison showing a larger value. Thus, for the comparison on technical change, the total profit of the biggest firm was larger for no technical change (NTC) runs in 16 cases, and smaller in 48 cases.

COMPARED ON TECHNICAL CHANGE (TC) vs NO TECHNICAL CHANGE (NTC)

	NTC : TC
Total profit of biggest firm	16 : 48
Profit of biggest firm as %age of industry total	5 : 59
Total profit for all firms	63 : 1

COMPARED ON WORLDVIEW

	II : IV
Total profit of biggest firm	72 : 24
Profit of biggest firm as %age of industry total	18 : 78
Total profit for all firms	95 : 1

COMPARED ON INITIAL MAXIMUM PLANT SCALE

	100 : 400
Total profit of biggest firm	55 : 41
Profit of biggest firm as %age of industry total	39 : 58
Total profit for all firms	77 : 19

COMPARED ON CAPITAL INTENSITY

	Low : High
Total profit of biggest firm	40 : 56
Profit of biggest firm as %age of industry total	66 : 30
Total profit for all firms	9 : 90

Significance levels are as in Appendix 9D. (N = 64 for the technical change comparisons; N = 96 for other comparisons.)

Note: the comparison between 4-firm and 16-firm simulation scenarios is not reported. This is because total industry capital will tend to be higher where more firms are operating, and the industry share of the largest will not be comparable when the number of firms varies.